NASA/CR-2000-210113

Examining INM Accuracy Using Empirical Sound Monitoring and Radar Data

Nicholas P. Miller, Grant S. Anderson, Richard D. Horonjeff, Sebastian Kimura,
Jonathan S. Miller, David A. Senzig, and Richard H. Thompson
Harris Miller Miller & Hanson, Inc., Burlington, Massachusetts

April 2000

The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA/CR-2000-210113

Examining INM Accuracy Using Empirical Sound Monitoring and Radar Data

Nicholas P. Miller, Grant S. Anderson, Richard D. Horonjeff, Sebastian Kimura,
Jonathan S. Miller, David A. Senzig, and Richard H. Thompson
Harris Miller Miller & Hanson, Inc., Burlington, Massachusetts

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NAS1-20102

April 2000

Acknowledgment

This study was made possible by the generous support of Mike McKee at Denver International Airport and of John Foggia (formerly) at Minneapolis International Airport. Through their agreement to make monitoring system data available, we have been able to develop the analyses presented in this report.

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The Federal Aviation Administration (FAA) has continually refined and made improvements to the Integrated Noise Model (INM) over the past two decades. The INM includes carefully developed algorithms that compute aircraft performance based on operating procedures, specific aircraft capabilities, and weather conditions. It includes sound level information for many aircraft types based on many years of measurement. Until recently, determining the accuracy of computed INM results has depended upon specific, occasional data collection efforts directed solely at determining such accuracy.[1][2][3][4][5][1]

Over the past 5 to 10 years, airports have begun installing and operating permanent noise and operations monitoring systems. These systems continuously collect sound measurement data at several permanent monitoring stations located around the airport, and may also collect and save flight tracking data from the FAA radar installation. These systems usually correlate, in an automated fashion, the measured sound levels with specific aircraft operations so that a database is constructed containing measured sound levels and flight tracks for most of the daily aircraft operations. Such databases present a new opportunity for examining noise levels actually produced by aircraft operations and comparing these measured levels with levels that the INM would compute for a similar set of operations.

HMMH installs and supports such noise and operations monitoring systems (the HMMH system is called ANOMS© - Airport Noise and Operations Monitoring System) at more than two dozen airports world-wide, and has been contracted by NASA to determine the technical feasibility of using the data from these systems to examine the accuracy of INM calculations. This report describes the study approach that has been developed and that will be followed to examine the use of sound monitoring and radar data acquired from such systems for comparison with INM results.

In general, the objective of this study was to develop and then apply an approach for comparing the measured Sound Exposure Levels, SELs, of specific aircraft types and operations with the INM generated SEL values for the same aircraft and operations. The first step in this effort was to use data from Denver International Airport (DIA) for developing and then applying the method. It was recognized that Denver is atypical in its high elevation (5431 MSL), but for reasons discussed in Section 3, Denver data were considered a reasonable starting point for analysis. Hence, the second step in the study was to apply the method to a second airport (MSP) with an elevation (840 MSL) significantly closer to sea level.

The study results presented here are intended to provide, after application to both the Denver and Minneapolis data, conclusions regarding:

1) a rigorous technical approach for examining the accuracy of the INM standard database through comparison with ANOMS data;
2) the accuracy of the INM insofar as it can be tested at two airports;
3) initial identification of possible sources of differences between INM computed and measure aircraft sound levels;
4) initial analyses of several of the possible causes of the differences.

[1] Numbers in brackets [ ] refer to endnotes listed in Section 8.

This report presents the approach used to assemble the necessary data, organize that data into a usable format, and analyze the data in a way that will permit comparison of parameters derived directly from the ANOMS installation at an airport (DIA and MSP) with the same parameters determined by the INM. Section 2 provides an overview of the total process. Section 3 describes the data assembly process, as applied to DIA. Section 4 presents the analyses that have been accomplished, including direct comparisons of INM calculated and ANOMS measured SEL at DIA. Section 5 presents the analyses and results for the MSP data, and compares them with the DIA results. Finally, Section 6 lists possible sources of the differences between INM computed and measured levels, and briefly examines three: flight procedures, airport temperature and airport elevation.

2. PROCESS OVERVIEW

2.1 Database Assembly

In general, the process involves collecting measured empirical data from ANOMS, feeding track and aircraft type information through INM 5.0 to yield computed values, and combining measured and computed data into one database in a form suitable for analysis with a standard statistical software package.[6] Figure 1 provides

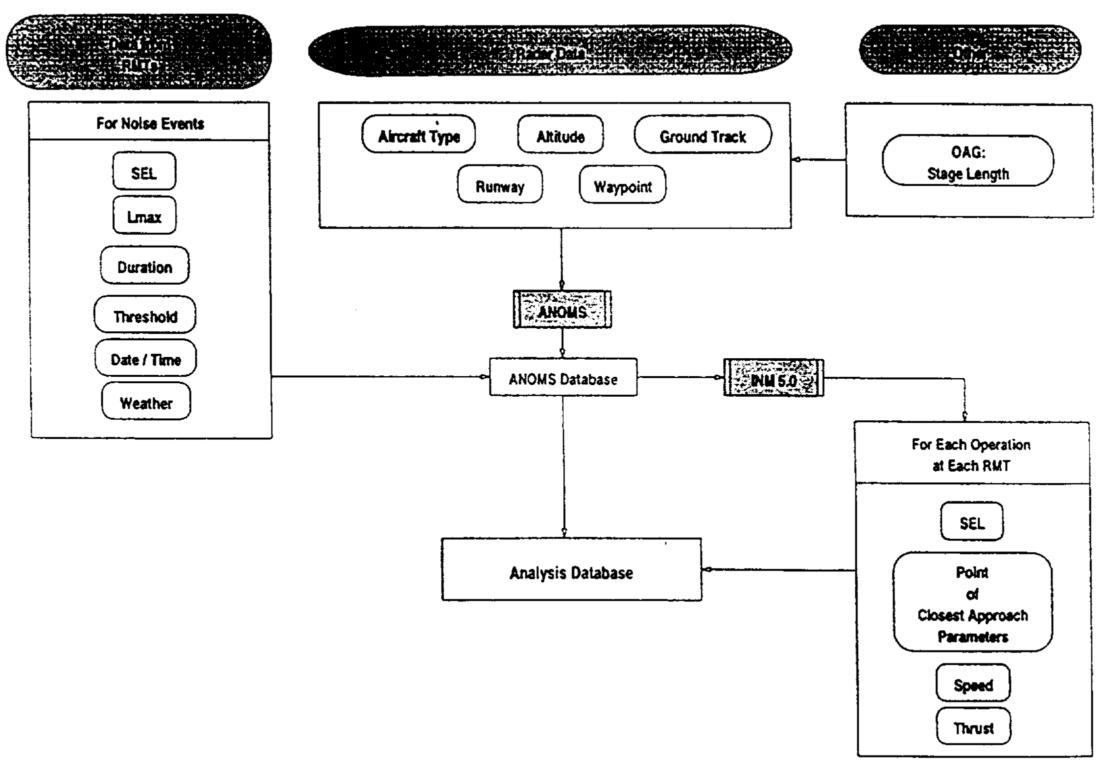

Figure 1. Schematic of Process Followed to Assemble Data for Analyses

a schematic overview of the data assembly process used for this study. The Remote Monitoring Terminals (RMTs) at 32 locations around DIA, Figure 2, provide the basic measured sound level data together with date/time and weather information.[2] The FAA radar system provides most of the details about each operation except for the stage length for departures (stage length is the distance a departure flies to the first destination airport) which is derived from Official Airline Guide (OAG) information that is imported into the system.

The RMTs collect one second A-weighted equivalent sound levels, and from these sound level time histories, ANOMS software applies several criteria to identify probable aircraft produced time histories or "noise events." These events are then automatically associated with a likely flight operation that produced each aircraft noise event, and with any logged complaints that were likely generated by the operation. These

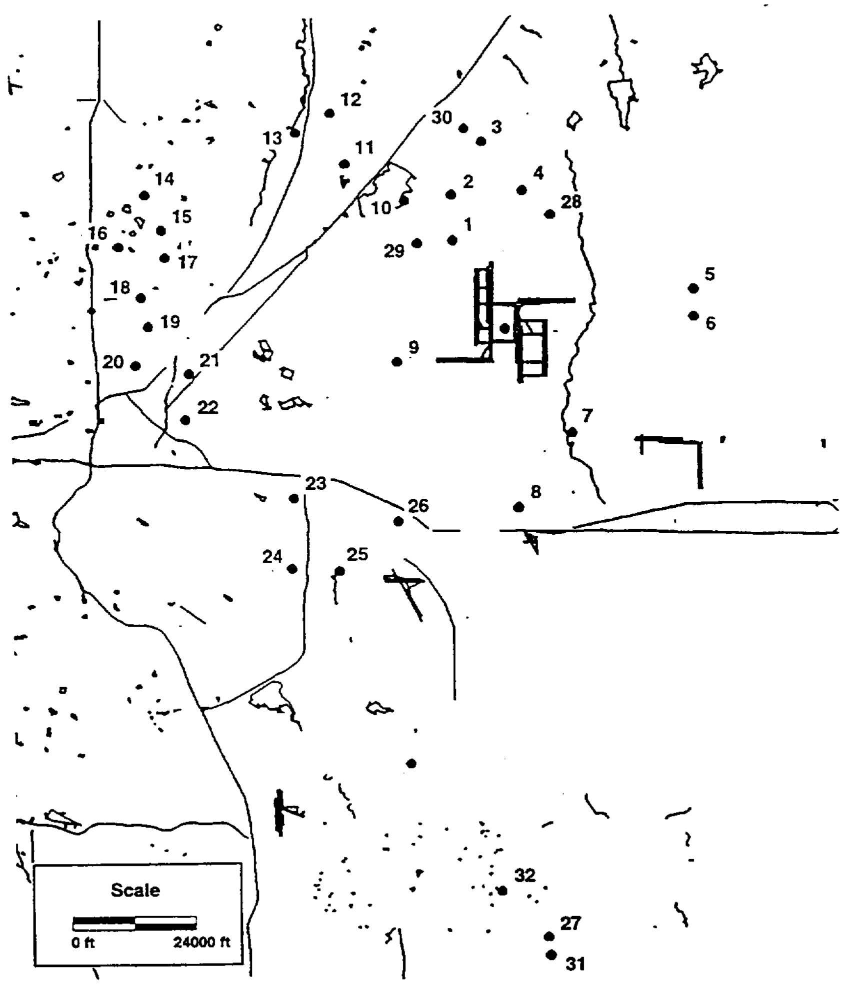

Figure 2. Remote Monitoring Terminal (RMT) Locations for Denver International Airport

---

2 Weather data are provided by instrumentation located at three of the RMTs. Also, monitors 27 through 32 were added after the collection of the data used in this study.

processes result in an extensive database relating aircraft operations, sound levels, weather conditions and complaints.

For this study, only operations that are associated with measured noise events are selected. For each such operation, track geometry, aircraft type, stage length and runway used are passed to INM 5.0, which is then run to compute SEL values at each RMT location. Finally, INM computed results are associated with the appropriate operation in the ANOMS database to yield the "Analysis Database" used for this study.

2.2 General Analysis Approach

The analysis is based on comparisons of INM computed and ANOMS measured SEL values, by aircraft type. The SEL metric is the fundamental building block of Day Night Average Sound Level, L_{dn} or DNL, and of the California Community Noise Equivalent Level, CNEL. If INM computed SEL and measured SEL agree reasonably for a given aircraft type under similar operating conditions, then INM computed DNL or CNEL contours should be reasonably realistic (assuming the measured SEL are accurate). By examining SEL rather than DNL, comparisons can be made without regard to the specific mix and number of aircraft that flew. DNL depends upon the number and type of aircraft, the runways used and flight tracks flown. By using only SEL, the analysis is independent of these variables and hence can more easily identify and analyze specific problems. For example, perhaps the INM calculated B727 departure SEL are very close in magnitude to measured B727 departures, but INM and measured B737 SEL are very different. This latter difference would be very difficult to identify if only DNL values were used. Hence, use of SEL permits the most efficient identification of differences by aircraft type, by type of operation.

The comparisons made here will be between "standard" INM computed levels and the measured levels. Each operation run through the INM is modeled with the power, speed and altitude profiles built into the INM; no modifications are made for altitudes or speeds as reported by the radar information. Only the airport elevation (5431 feet MSL) and temperature (59°F) are actually entered into the INM as a locally determined variable. This approach is intended to address the accuracy of INM modeling when only the flight track (ground track), aircraft type and stage length are provided. In other words, if an airport is modeled with accurate tracks, aircraft types, stage lengths, and airport elevation and temperature, will the resultant contours be acceptably accurate? Ultimately, such an approach will determine whether "standard" modeling of operations is sufficient, or whether additional modeling data or changes to the INM are necessary to produce accurate contours. All comparisons, naturally, will be made at the specific RMT locations shown in Figure 2.

The primary assumption made is that the measured values of SEL are accurate and represent the sound levels produced by each aircraft operation. The Denver system has been validated by comparison of ANOMS automated results with simultaneous on-site observations and measurements. These validation comparisons were used to adjust the parameters that ANOMS uses to identify aircraft noise events and to associate events with specific operations. Acoustic and electronic checks are done automatically four times per day, and each microphone is manually checked annually. The microphones are sent to a laboratory for full calibration every other year. In general, the system works well at associating aircraft produced noise events with aircraft operations. Weaknesses appear, however, in occasionally associating non-aircraft produced noise events (community noise levels and wind induced noise levels) with aircraft operations. As a result, some incorrect SEL values can be expected in the ANOMS database. To minimize the likelihood of including such values in the analysis, several additional filters are explored to determine whether likely errors can be removed.

2.3 Comparisons of Computed and Measured SEL

Three types of comparisons are made: 1) a general analysis of ANOMS data for inaccuracies and for utility in later analyses; 2) analysis of methods (filters) to use for removing categories of data that may be in error or not useful in the analysis; 3) calculation of "figures of merit" that quantify, for each aircraft type and type of operation (arrival or departure) the difference between INM calculated SEL and measured SEL. The first comparison is described in detail in Sections 4.1 and examines whether the ANOMS database has any errors that could significantly bias the comparisons with INM calculated results. Second, Section 4.2 focuses on the use of additional filters on ANOMS data to explore the removal of questionable ANOMS data or to remove data that are not used in the present analysis.

The third comparison, Section 4.3, develops single number measures, in dB, with 95% confidence limits, quantifying the difference between INM calculated SEL and ANOMS measured SEL. These single numbers, termed here "figures of merit" permit rank ordering of differences and are developed for each of six specific aircraft types, by type of operation. The figures of merit are developed for differences in energy average SEL. Use of energy averages reveals the significance of any differences between calculations and measurements in terms of long-term sound exposure, such as DNL, which are computed using sound energy.

3. DATA ASSEMBLY

Data are assembled first from the ANOMS installation at Denver, and then used to generate data with the INM, version 5.0. The ANOMS and INM data are then assembled into a single database for analysis.

3.1 ANOMS

3.1.1 Denver System Operation

The Denver installation has an unusually large number of RMTs (currently 32), to our knowledge exceeded in number by only one or two other installations. These RMTs are also distributed at distances ranging from roughly one to 10 miles from the airport, see Figure 2. Hence, sound levels are measured both at distances common for measurements and at distances well beyond the extent of most 65 DNL contours and noise measurements. The 26 original RMTs have been operational and collecting data since before the airport was opened in February 1995. At each RMT, one-second A-weighted L_{eq} values are measured and stored for daily down-load to the central processor. These data are then processed to yield identified noise events that have a high probability of being produced by aircraft overflights. Weather sensors at three RMTs (11, 18 and 26, see Figure 2) associate wind speed and direction, temperature, humidity and pressure with each event based on the time of the event.

The system also acquires daily radar data from the ARTS (Automatic Radar Terminal System). The radar data contain parameters giving aircraft operator, aircraft type, flight plan information and aircraft position as a function of time. The position information is time stamped and is recorded each antenna rotation, about once every 4½ seconds. ANOMS uses this information to process the noise events, and associates one or more aircraft operations with each event. Algorithms used in the matching of operations (radar tracks) and measured noise events include such parameters as time of event and time of operation, aircraft type, location, orientation, rate of climb and speed. Additionally, OAG data provides the stage length for each departure.

Once operations are associated with noise events, "point of closest approach" or PCA parameters are calculated. These parameters include (for the point of closest approach): slant distance from the aircraft to the

RMT, aircraft altitude, elevation of the aircraft above the horizon with respect to the RMT, and range or distance over the ground from the RMT to the point of closest approach. The point of closest approach is simply the radar returned location that has the shortest vector to the RMT.

3.1.2 Denver ANOMS Data

For this study, measurement data have been assembled for an average of three days each month for the twelve month period of April 1995 through March 1996. Table 1 gives the days selected and the number of operations available each day for analysis. These are the operations that are associated with at least one measured SEL at one RMT and that included sufficient data to be modeled in the INM. The days were chosen randomly in contiguous pairs of three that included one weekend day to insure the ratio of week days to weekend days was at least 2:1 (close to the true ratio of 2½:1). June data did not include sufficient identification of whether the operations were arrivals or departures, so two other months were randomly selected, one to provide one day, March, 1996, and one to provide two days, December, 1995. Contiguous days were used to simplify the extraction process.

Tables 2 and 3 give the number of departure and arrival operations in the Analysis Database by type of aircraft as given in the ARTS data. (These type designations are converted to INM type designations for modeling, see Section 3.2.) Note that in these tables only aircraft types for which there are more than about 100 operations in the data base are listed. More arrival operations and arrival types of aircraft are reported most likely because RMT locations and flight tracks make measurement and identification of arriving aircraft easier than measurement and identification of departing aircraft. It is also likely that spacing of aircraft arrivals and lower altitudes at considerable distances from the airport mean that RMTs in line with the runways can measure more arrivals than departures.

Table 1. Days from which ANOMS Data were Assembled for Analysis

Date		Number of Operations in Analysis Database
April 6, 1995	Thu	1339
April 7, 1995	Fri	1347
April 8, 1995	Sat	1232
May 11, 1995	Thu	718
May 12 1995	Fri	1359
May 13, 1995	Sat	1130
July 23, 1995	Sun	1598
July 24, 1995	Mon	1344
July 25, 1995	Tue	1398
August 17, 1995	Thu	1534
August 18, 1995	Fri	1419
August 19, 1995	Sat	1422
September 3, 1995	Sun	1125
September 4, 1995	Mon	1279
September 5, 1995	Tue	1506
October 15, 1995	Sun	1717
October 16, 1995	Mon	1212
October 17, 1995	Tue	1897
November 16, 1995	Thu	1100
November 17, 1995	Fri	1578
November 18, 1995	Sat	887
December 14, 1995	Thu	1274
December 15, 1995	Fri	1246
December 16, 1995	Sat	929
December 17, 1995	Sun	1036
December 18, 1995	Mon	1038
January 18, 1995	Thu	1667
January 19, 1995	Fri	1331
January 20, 1995	Sat	1308
February 1, 1996	Thu	1468
February 2, 1996	Fri	1349
February 3, 1996	Sat	1370
March 7, 1996	Thu	1217
March 8, 1996	Fri	1318
March 9, 1996	Sat	1115
March 10, 1996	Sun	980
Total Records		46787

Table 2. Departures by ARTS Aircraft Type

ARTS Aircraft Type	Number of Departures
M80	1592
72F	91
D8F	119
BE1	503
D10	962
72S	6286
EM2	244
73S	4292
32S	261
DH8	142
320	232
733	3164
734	252
735	1370
757	1059
TOTAL	20569

Table 3. Arrivals by ARTS Aircraft Type

ARTS Aircraft Type	Number of Arrivals
B727	578
M80	1088
SW4	144
75F	176
BE02	1038
D8F	98
DC9	173
LR25	135
BE1	2064
D10	1128
72S	5171
E120	138
EM2	335
73S	3271
32S	501
B737	107
BE99	123
320	313
733	4075
734	289
735	1884
757	1888
TOTAL	24717

The analysis will focus on jet aircraft types for which the data base contains the largest numbers of operations. Table 4 lists the selected aircraft types, as designated in the ARTS data, and the number of departures and arrivals in the ANOMS data base for that type. As shown, some ARTS designations are combined, for example 72S and B727 are both ARTS designations for Boeing 727 aircraft. Also, all 737-300, -400 and -500 aircraft will be treated as one type since they have very similar engines, and since the INM models them as producing very similar sound levels (within about 1 dB).[3]

Table 4. Aircraft Types and Numbers of Operations that will be Analyzed

Aircraft Type (ARTS Designation)	Number of Departures	Number of Arrivals
M80	1534	1085
D10	962	1120
72S / B727	6286	5693
B73S / 73S / B737	4277	3401
733 / 734 / 735	4718	6188
757 / B757	1038	1896

The ANOMS data base provides many parameter values for each of the operations. The following paragraphs give the name as it appears in the database and describe each of the parameters that will be available for use in the analysis.

OPNUM

This is a unique number assigned by ANOMS to each radar tracked operation. It is used in this data base assembly to tie the ANOMS data with the data generated for the operation by the INM. When the INM is run for the specific flight track, the flight track name (TRK_ID1, see Section 3.2.2) is derived from this number so that the INM results that appear in the DBF file (GRID_DTL) can be associated through this track name with the ANOMS data for the same operation.

---

[3] The INM, with data base 11, computes the following SEL values:

INM Number	INM Aircraft	Departure SEL @ 30k ft. from brake release	Arrival SEL @ 10k ft. from landing threshold
35	737300	78.1	90.0
36	7373B2	78.0	90.0
85	737400	79.7	90.1
86	737500	78.3	90.0

ACTUALTI

This is the day/month/year of the start of the operation.

STAGE

The certification stage of the aircraft.

RMTID

The number of the remote monitoring terminal (RMT) at which the given SEL was measured.

SEL_M

The SEL measured at the identified RMT for the operation.

NUMOFSEL

The number of SEL values reported for the specific operation at the given RMT. Aircraft operations sometimes can produce more than one SEL (noise event) at a single RMT. The combination of changing sound level as the plane passes by, usually on departure, and the algorithms used to identify "noise events" sometimes result in two SEL values being produced by one operation. Since the total sound energy produced is most likely the sum of all SEL, the assembly of the ANOMS data base sums the SEL values when there is more than one, reports the sum as SEL_M, the number of SEL values summed, NUMOFSEL, and the maximum SEL, see MAXSEL below.

MAXSEL

This is the highest value SEL that was reported for the operation. Together with NUMOFSEL and SEL_M, an assessment may be made of how many SEL values were used to compute SEL_M, and how important they were. In general, the data base had very few operations with more than one SEL measured, if there was more than one, it was usually two, and the maximum SEL was only a few tenths of a decibel less than the sum. Hence, in these cases, the maximum SEL included most of the sound energy measured for the operation.

WINDS

The wind speed in miles per hour at the time of the noise event. Wind data are collected at RMTs 11, 18 and 26. Wind speed and direction are sampled once per second and averaged over a minute for the data base. The weather data used at a particular RMT is that measured at the nearest of these three locations.

WINDD

The direction in degrees relative to true north from which the wind was blowing at the time of the event.

TEMP

Temperature in degrees F. Temperature, humidity and pressure are measured at only RMT 26. They are sampled once per minute and averaged over an hour for the data base.

HUMIDITY

Relative humidity at the time of the event.

PRESSURE

Atmospheric pressure in inches of mercury at the time of the event.

OP_TYPE
Arrival or departure.

RWY_ID

Runway used by the operation.

OPER
Operator of the aircraft, usually an airline, in three letter code.

TYPE
Aircraft type as given by the ARTS.

STAGELEN
INM stage length. This is derived from Official Airline Guide data for the specific flight.

STARTS
The start time of the noise event as hour:minute:second.

END
The end time of the noise event as hour:minute:second.

DURATION
Difference between END and STARTS, in seconds.

MAXLEVEL
The maximum A-weighted level for the noise event.

THRESHOL
The threshold level, in A-weighted decibels, that existed at the time the noise event was determined to commence. For the Denver installation, ANOMS uses a variable threshold level based on ambient levels to maximize the probability of capturing low level events.

PCADISTA
The slant distance, in feet, from the RMT to the point of closest approach (PCA) of the aircraft's flight track. The PCA is determined by computing the vector lengths from each radar return along the track to the RMT location, and selecting as PCA the return with the shortest vector. That vector is the PCADIST. All PCA calculations use the elevation of the specific RMT and the relative altitude of the track points.

PCAALTIT
The altitude of the aircraft above the RMT elevation at the PCA.

PCARANGE
The horizontal distance from the RMT to the PCA.

PCAELEVA

The angle of the PCA above the horizon with respect to the RMT.

TRK_DIST

This parameter gives the distance along the flight track, from either the landing end for arrivals, or the takeoff end for departures, to the PCA.

3.2 INM

3.2.1 Method

Because the INM accomplishes all calculations through the use of various input and output files (in a standard data base format), it is possible to construct the input files with any appropriate method and run the INM. Accordingly, the input data necessary to run the INM was fed from the ANOMS data base to INM input files. The INM was run, and the output information for each operation taken and combined with the ANOMS data base to produce the Analysis Database which is used for all analyses. The following section describes the INM files that were used and the primary fields that were either filled from ANOMS data, or used to construct the Analysis Database.

3.2.2 INM Files Used

First, basic information for DIA was used to create a "Study Setup." Some data were entered manually using the INM 5.0 user interface, while other data were fed directly into the appropriate file format and designation. Airport origin, altitude and all aircraft types were entered into file study.inm. Note that the Denver airport actual elevation was used as the airport altitude in all INM runs. The RMT locations were available as latitudes and longitudes and were entered into file loc_pts.dbf, along with the altitude of each RMT. In order to compute SEL values for each flight at each RMT, the coordinates of each RMT had to be transformed to nautical miles from the airport origin and entered manually into the file grid.dbf. The transformation was checked by plotting both on the screen at the same time. Other specific files and the parameters used are listed below.

TRACK

This file contains information about each track to be modeled, including the runway used, whether the operation is an arrival or departure, a track identifier, and the percent use of the track. ANOMS data for one day of operations were fed automatically to the appropriate fields in this file (roughly 1000 tracks). Each track was input as having one operation (100% use), or, in other words, each single departure or arrival operation had its own track. This file also identifies the fact that the track (TRK_TYPE) is points (P).

Actual ground tracks, as reported by the radar data, were used to model each operation. This analysis attempts to control for all variables possible so that any differences between calculated and measured levels are a result of as few factors as possible. Some examinations of INM calculated and measured levels have used nominal flight tracks[5], but so doing adds the variable of how well the nominal track duplicates the actual track, and some of the variance of calculated from measured levels will be a result of incorrect track location. Use of actual ground tracks removes track location as a source of error.

Of particular importance is the track identifier, TRK_ID1. As noted under OPNUM in Section 3.1.2, this parameter uniquely identifies an operation and permits the output of the INM to be associated with the correct ANOMS data.

TRK_SEGS

This file, in addition to carrying most of the same information as given in TRACK, contains all the x- and y- coordinates for the tracks. Correct translation of the flight tracks from ANOMS to INM format was verified by producing plots of sample tracks at the same scale from both ANOMS and INM.

OPS_FLT

The number of flights on each track is identified in this file. Each modeled track contained only one operation, since each track was the actual one flown by a single arrival or departure. Note that the profile stage identifier (PROF_ID2) for departures was the stage length as provided by the ANOMS data base for each departure operation, see STAGELEN, Section 3.1.2.

This file associates a specific aircraft type with each track modeled. The ANOMS data base does not supply the INM aircraft type, but rather the three letter code assigned to the aircraft in ARTS. This ARTS type is converted to INM type by a statistical assignment process. For Denver, each airline's fleet mix is used to quasi-randomly associate an INM type with each operation. For example, if United Airlines flies 25% B727-200 / JT8D-15QN and 75% B727-200 / JT8D-17 to Denver, then 25% of all UAL 727 operations reported by ARTS will be assigned to INM type 727Q15 and 75% to 727D17. For airlines whose Denver fleet mix is unknown, that airline's total fleet mix is used. For airlines whose total fleet mix is unknown, the overall Denver fleet mix is used. In terms of the analysis, not knowing the specific aircraft model / engine type will increase the scatter of the data, to the extent that different models / engine types produce different sound levels.

OPS_CALC

Because no subtracks are used, this file provides basically the same information as provided by OPS_FLT.

GRID_DTL

All INM output of interest to this study is provided by GRID_DTL. For each modeled operation, it provides:

- **SEL** as computed for each RMT, for this study called **SEL_C**,
- **TRK_ID1**, used to associate the computed SEL with the corresponding operation (OPNUM) in the ANOMS data base.
- **DISTANCE**, the slant distance from the RMT to the point of closest approach (PCA) or closest point of approach (CPA), comparable to **PCADISTA**, see Section 3.1.2.
- **ALTITUDE**, the altitude of the aircraft at the PCA, comparable to **PCAALTIT**,
- **ELEV_ANG**, angle of the aircraft above the horizon at the PCA, as viewed from the RMT, comparable to **PCAALTIT**,
- **SPEED**, speed of the aircraft at the PCA,
- **THR_SET**, the modeled thrust setting at the PCA.

3.3 Data Organization

A data base query is performed to build the Analysis Database from the ANOMS data base and from the INM file GRID_DTL. The query uses the track identifier, TRK_ID1, in the INM output, to pick the appropriate record from the ANOMS data base and to assemble all the relevant ANOMS parameters listed in Section 3.1.2 with the relevant INM parameters in the GRID_DTL output file. The result, for this study, is a 25 megabyte dbf file with some 48,000 records, one for each aircraft operation, that may be analyzed with a statistical software package.

4. DATA ANALYSIS

Four levels of analysis will be pursued. The first is a general exploration of variables to identify any obvious errors in the data, and to determine the usefulness of specific variables. The second level of analysis, "cleaning" seeks to eliminate classes of data points that have the highest likelihood of being incorrectly measured, or not of interest at this time. Third, the "figures of merit" are developed that quantify the differences between INM calculated and ANOMS measured SEL values. These first three are described in this section. Finally, several types of analyses are conducted to identify possible sources of the differences between calculated and measured values. These last analyses are described in Section 6 and lead to the conclusions and recommendations in Section 7.

4.1 General Exploration for Errors and Utility

4.1.1 Point of Closest Approach Parameters

<u>Analysis</u>

As described, flight track location and flight information were transferred automatically from ANOMS to INM. To insure that this transfer was accurate, that SEL values are computed at locations comparable to the measurement locations, and to check the general reliability of the point of closest approach algorithms used in ANOMS, several comparisons were made. For one day of 72S data (6 April 1995), a selection of operations as measured at all monitors were used to compare INM and ANOMS point of closest approach parameters. This limited data set was used so that individual flight tracks and altitude profiles could be easily identified and examined in detail, if significant differences were found between INM and ANOMS data.

Figures 3 and 4 compare INM and ANOMS computed slant distance values at the point of closest approach (PCA) for 72S departures and arrivals measured on this day in April. Figures 5 and 6 compare ANOMS and INM altitudes, while Figures 7 and 8 compare elevation angles for each operation. Note that all altitudes are expressed as feet above field level. All these figures show a high degree of correlation between the INM and ANOMS values, but with varying amounts of scatter. Because the ground tracks were separately checked and should be identical for ANOMS and for the INM, scatter should be a result primarily of different altitude profiles.

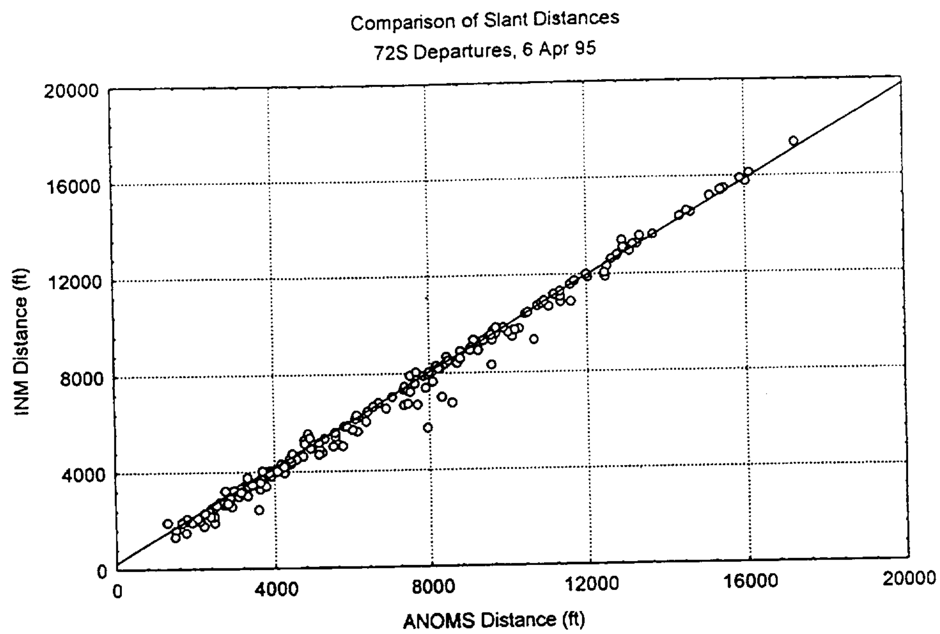

Figure 3. Comparison of INM and ANOMS Computed Slant Distances -Departures

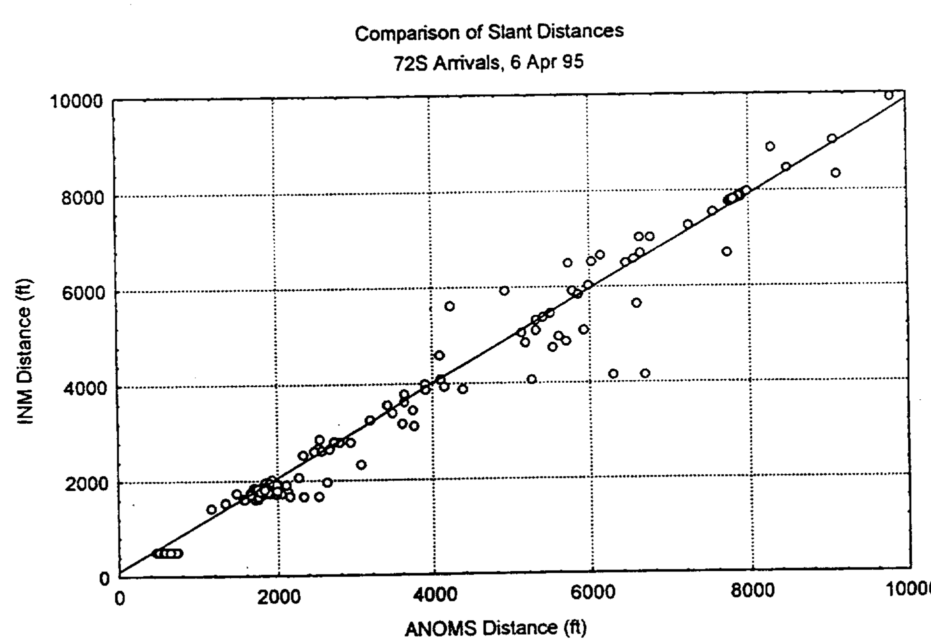

Figure 4. Comparison of INM and ANOMS Computed Slant Distances - Arrivals

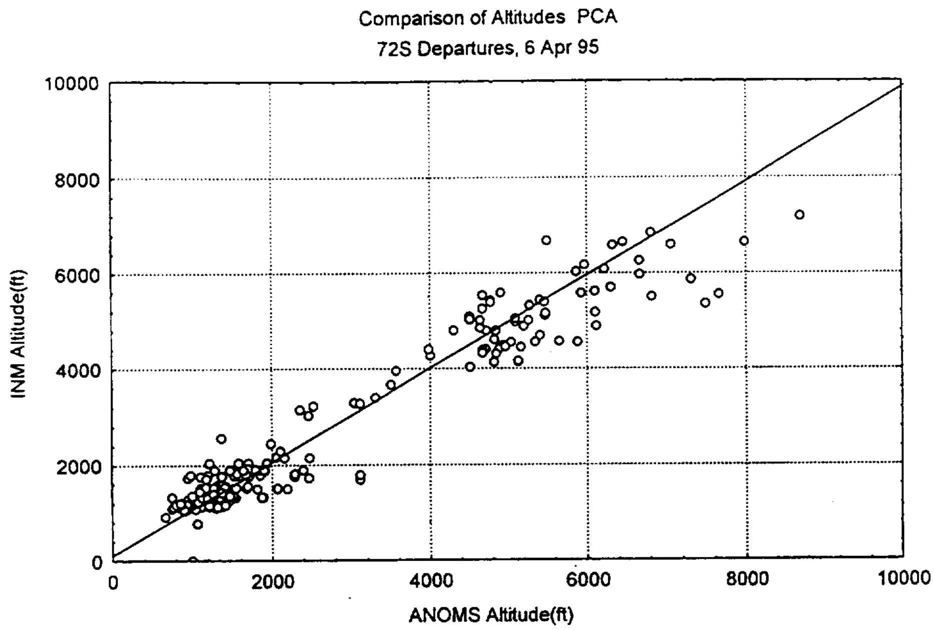

Figure 5. Comparison of INM and ANOMS Computed Altitudes - Departures

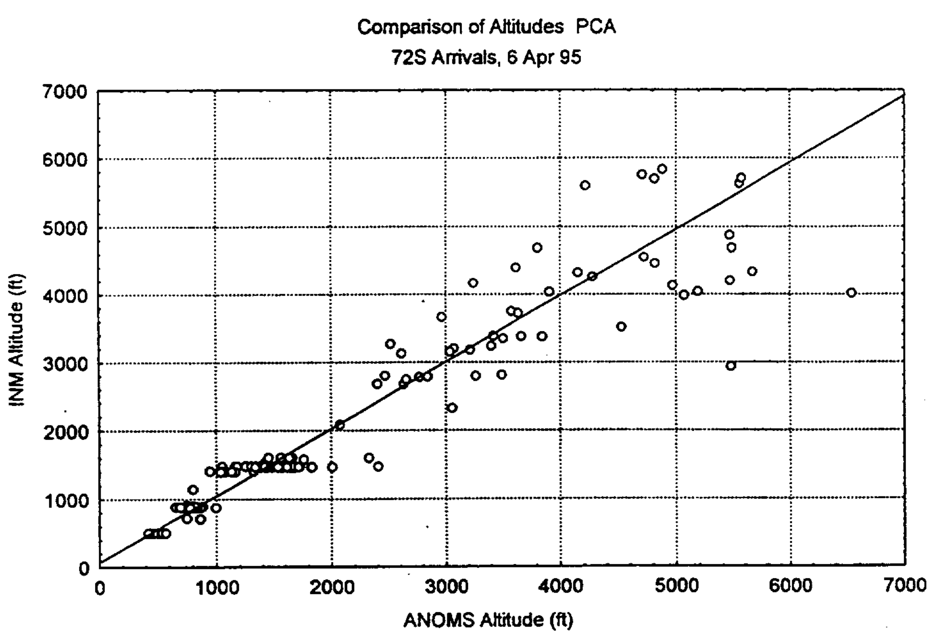

Figure 6. Comparison of INM and ANOMS Computed Altitudes - Arrivals

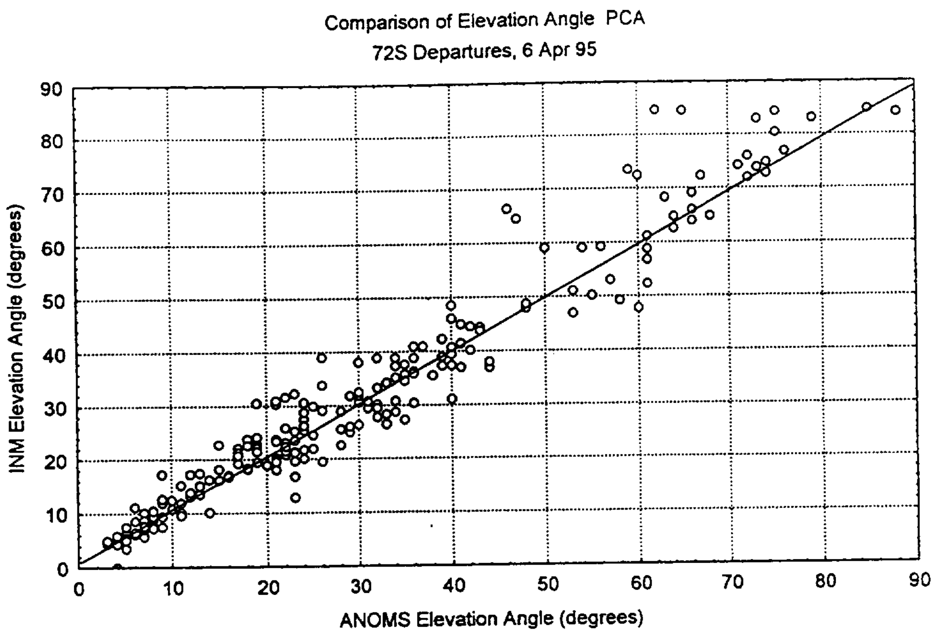

Figure 7. Comparison of INM and ANOMS Computed Elevation Angles - Departures

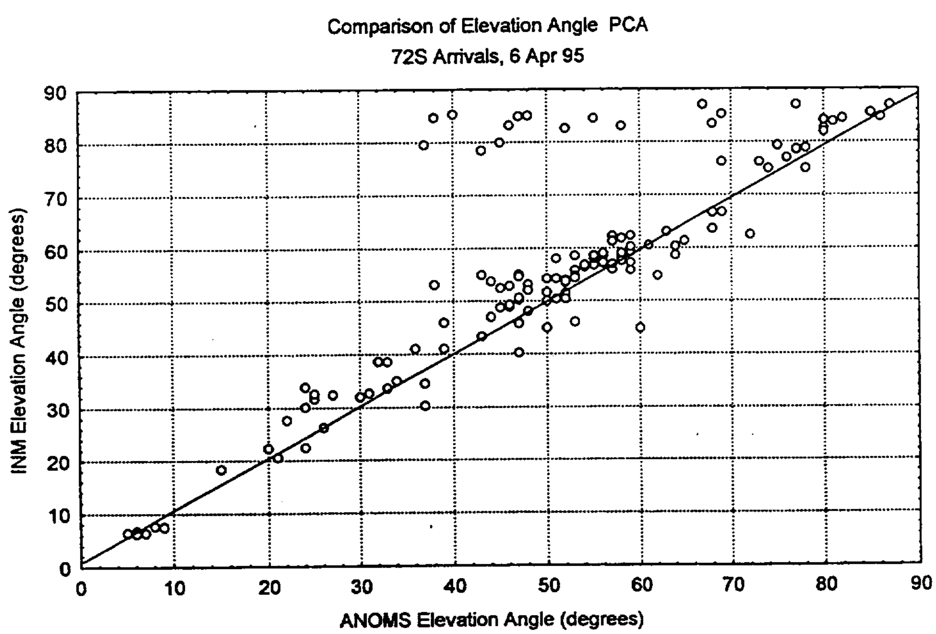

Figure 8. Comparison of INM and ANOMS Computed Elevation Angles - Arrivals

Figures 9 and 10 show the altitude profiles for these departure and arrival operations, respectively, and compare them with corresponding representative INM altitude profiles. For departures, Figure 9 shows that ANOMS altitudes tend to be lower than INM altitudes at altitudes of roughly 2000 to 3000 feet above the airport, and Figure 5 supports this tendency. As altitudes increase above 6000 feet, Figure 9, ANOMS altitudes tend more often to exceed INM altitudes, and this trend is suggested in Figure 5. Also, Figure 9 shows that ANOMS altitudes vary from the INM altitudes by about ±1000 feet or less, for under 100000 feet cumulative flight distance. Again, Figure 5 data demonstrate this magnitude of scatter. Arrivals, Figure 10, show greater variation of ANOMS altitudes from the INM altitudes, being as much as ±2000 feet for similar flight distances. Figure 6 data show this greater scatter as well.

Elevation angle comparisons of Figures 7 and 8 also show high correlation, except when the INM elevation angle is close to 90 degrees, the ANOMS elevation angle can be much less, particularly for arrivals, Figure 8. Figure 11 presents the difference between INM and ANOMS elevation angle as a function of ANOMS slant distance. (In general, the ANOMS slant distances will be considered to be more accurate since they are computed for the actual ARTS track / profile, rather than for the nominal INM track / profile.) This figure shows the clear trend that for shorter slant distances (when the aircraft is close to the monitor), the ANOMS elevation angle tends to be considerably less than the INM angle.

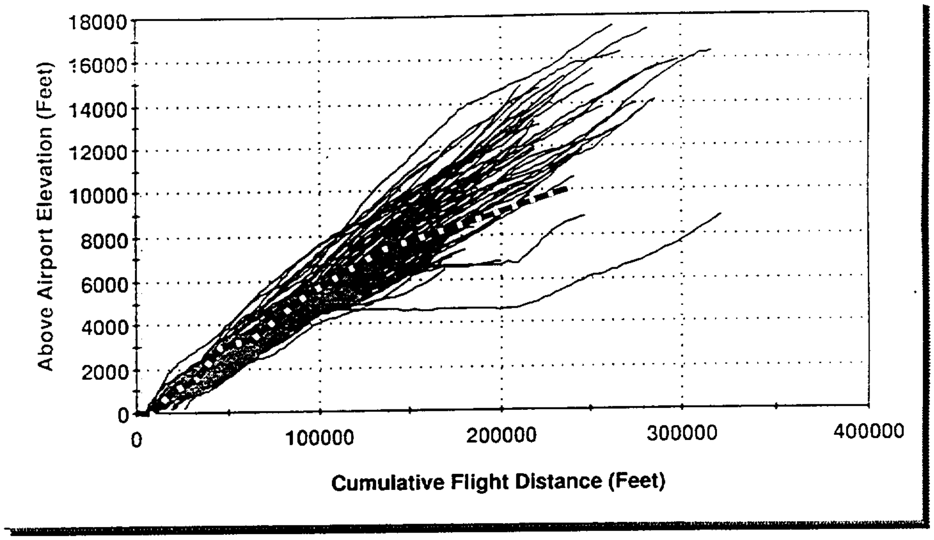

Figure 9. Comparison of ANOMS (ARTS) Departure Altitudes with INM 727Q15

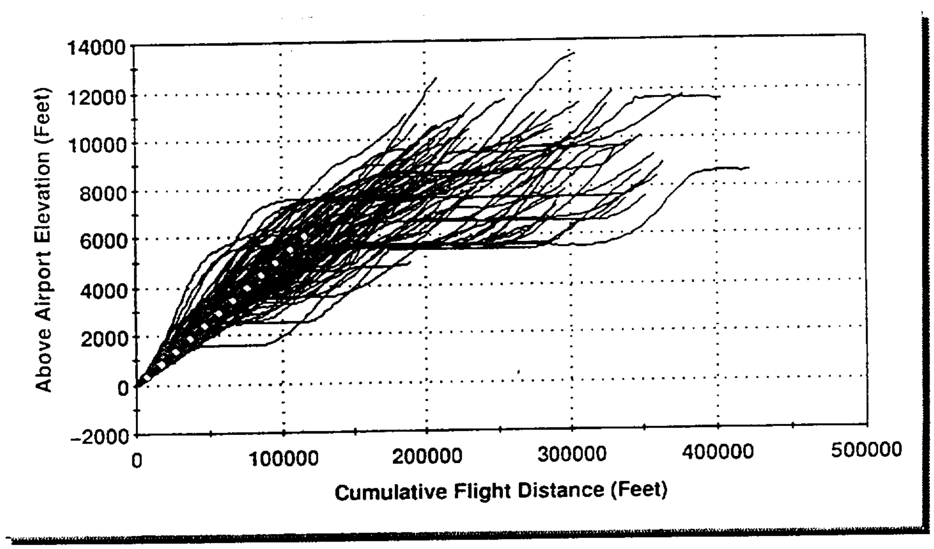

Figure 10. Comparison of ANOMS (ARTS) Arrival Altitudes with INM 727Q15

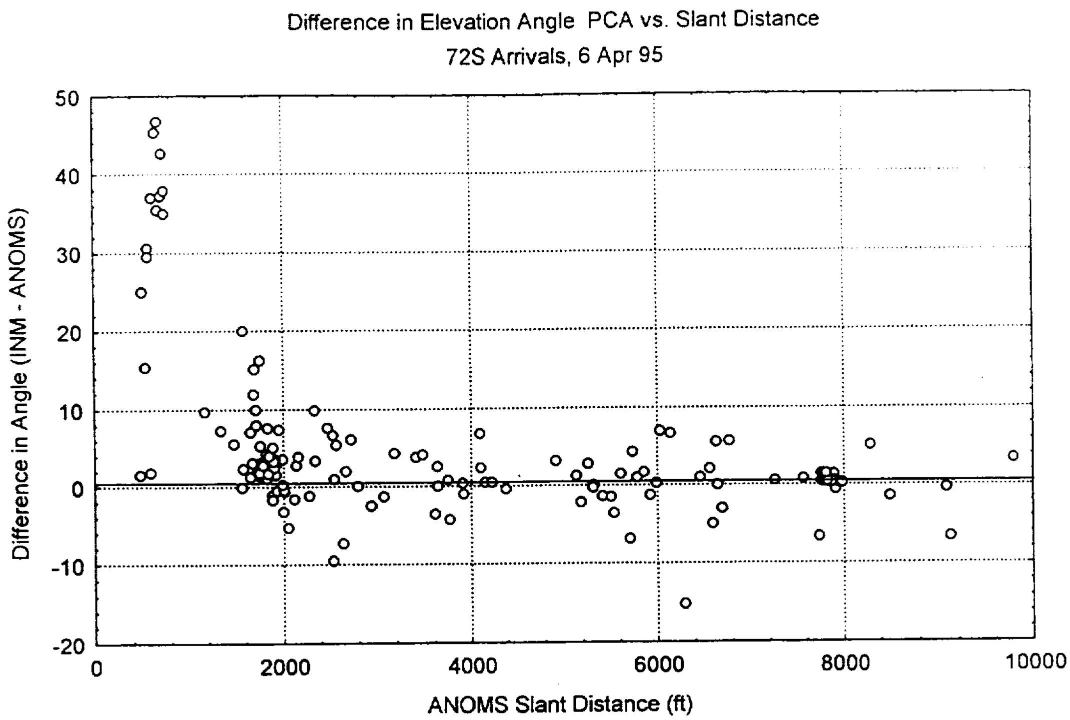

Figure 11. Difference Between ANOMS and INM Elevation Angle as a Function of ANOMS Slant Distance

The ANOMS algorithm used to compute the angle is responsible for this incorrect angle at shorter slant distances. As discussed in Section 3.1.2, the ANOMS PCA calculations are made using the actual track points returned by the ARTS. This approach means that when the aircraft is close to the ground and close to the RMT (i.e., nearly overhead), the closest track point may not be over the RMT, but could occur before or after the plane passes over. Hence, the elevation angle will not be the maximum angle (close to 90 degrees), but somewhat less, and even considerably less if the aircraft is low.

In general, Figures 3 through 8 show high correlation between the INM and ANOMS values for each parameter, recognizing that perfect correlation would mean that every point lies on the diagonal lines of the plots. Some differences between the INM and ANOMS slant distances should be expected since the INM altitude profiles will not always match the actual ARTS altitude profiles. Figures 9 and 10 compare the ARTS departure and arrival altitude profiles with those of a representative INM aircraft used to model 72S operations. For both types of operations, and especially arrivals, ARTS reported altitudes may be quite different from the INM altitude for a given point along the track.

Conclusions

Either INM or ANOMS slant distances could be used in further analysis, but preference will be given to the ANOMS slant distance parameter since it is based on the actual track and altitude flown. Only at relatively short slant distances (under 2000 feet, see Figures 4 and 11) may it be biased as higher than actual.

ANOMS altitudes should be used in analyses as necessary, rather than INM altitudes. As with ANOMS slant distances, they can be expected to be less accurate at altitudes less than about 2000 feet, but they are unlikely to biased toward either higher or lower than actual.

INM altitude profiles appear to be reasonable representations of average 727 operations, see Figures 9 and 10. The comparison of INM and ANOMS altitude profiles are explored further for other aircraft types in the Denver database (in Section 4.3.4 and Appendix B).

4.1.2 Weather Data

Analysis

Three RMT's contain weather sensing equipment. Figure 12 is one day of wind speed and direction data (one minute averages). When wind speed is low, direction, as seen, is often highly variable. When wind speeds rise, direction becomes more constant. Figures 13 and 14 provide example days of pressure and temperature data.

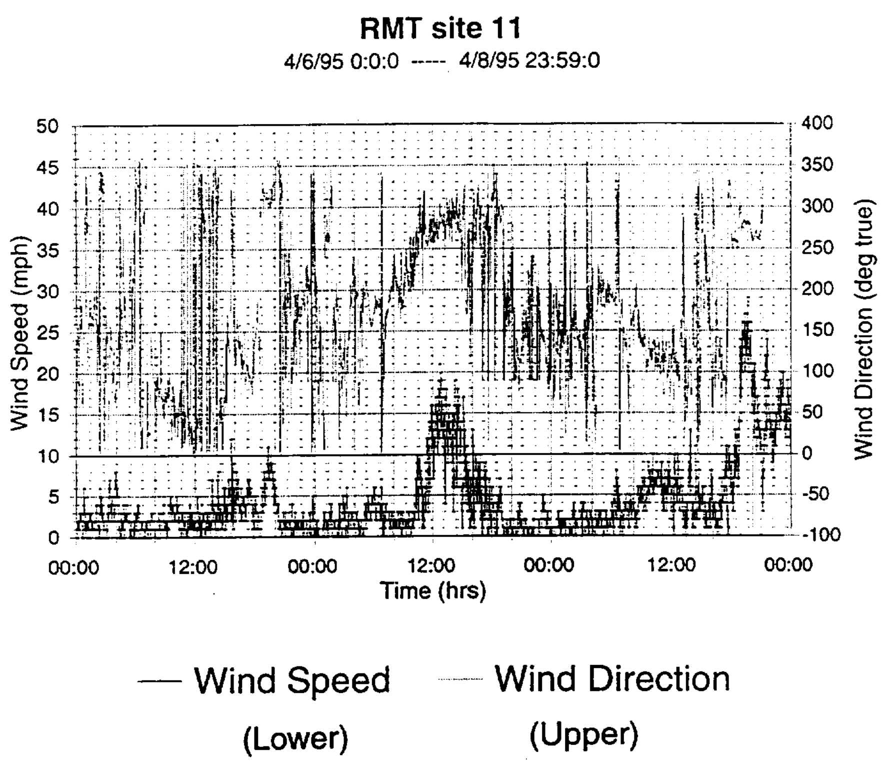

Figure 12. Typical Wind Speed and Direction Data - RMT 11

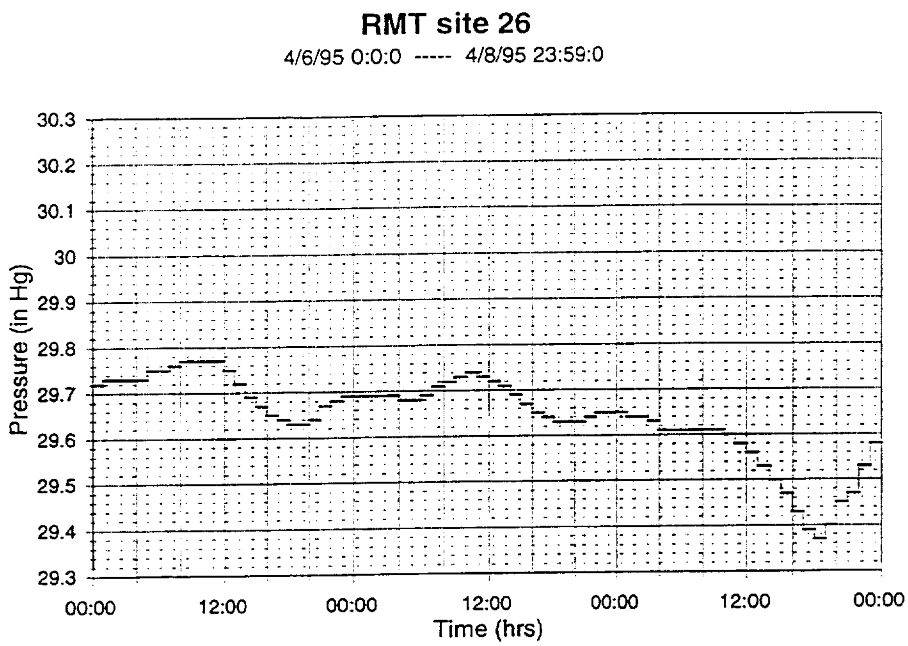

Figure 13. Typical Atmospheric Pressure Data

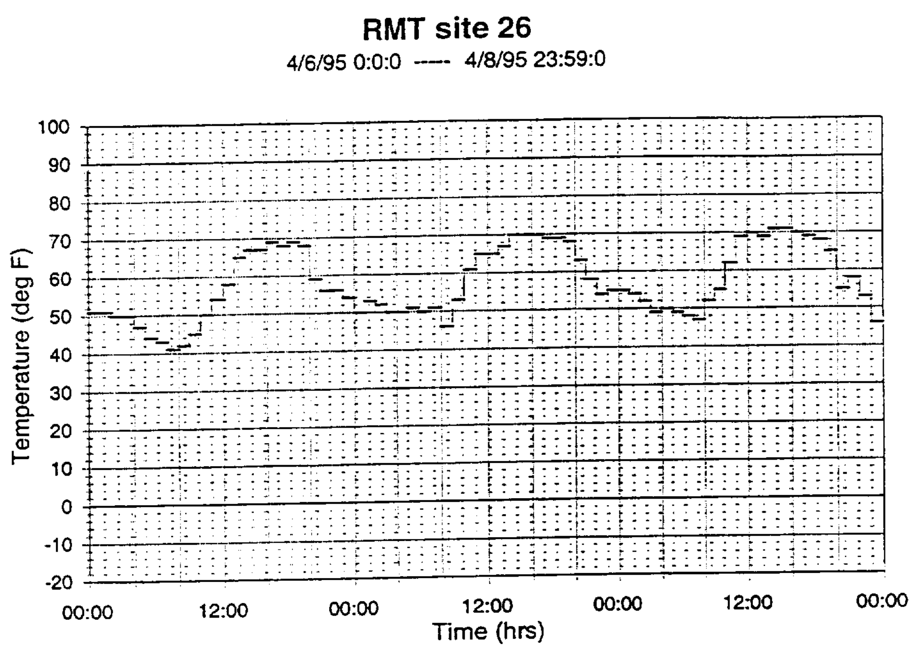

Figure 14. Typical Temperature Data

During testing and verification of the ANOMS installation at Denver, several series of on-site observations and measurements were conducted to verify / adjust the "noise event" identification algorithms and associated parameters. Though most types of incorrectly identified noise events were corrected, wind generated noise in the microphone can still be erroneously categorized as an aircraft produced noise event. If that wind produced noise happens to fall at a time when an aircraft is sufficiently close, and meets a number of criteria, the wind event may be associated incorrectly with an aircraft operation. The wind data was examined to determine whether it might serve to help identify these incorrect events.

However, as mentioned in Section 3.1.2, wind data are collected at only three RMTs, numbers 11, 18 and 26, and the wind information from these three is associated with events measured at other monitors. Hence, true wind information is not known at each RMT, and, in particular, wind gust information is not known. To explore whether wind speed data collected at one RMT predicts wind speed data at another RMT, wind data from wind speed data taken simultaneously at RMTs 26 and 11 were plotted in Figure 15. Clearly, windspeeds at these two locations are uncorrelated, except perhaps at very low speeds (which are not of interest).

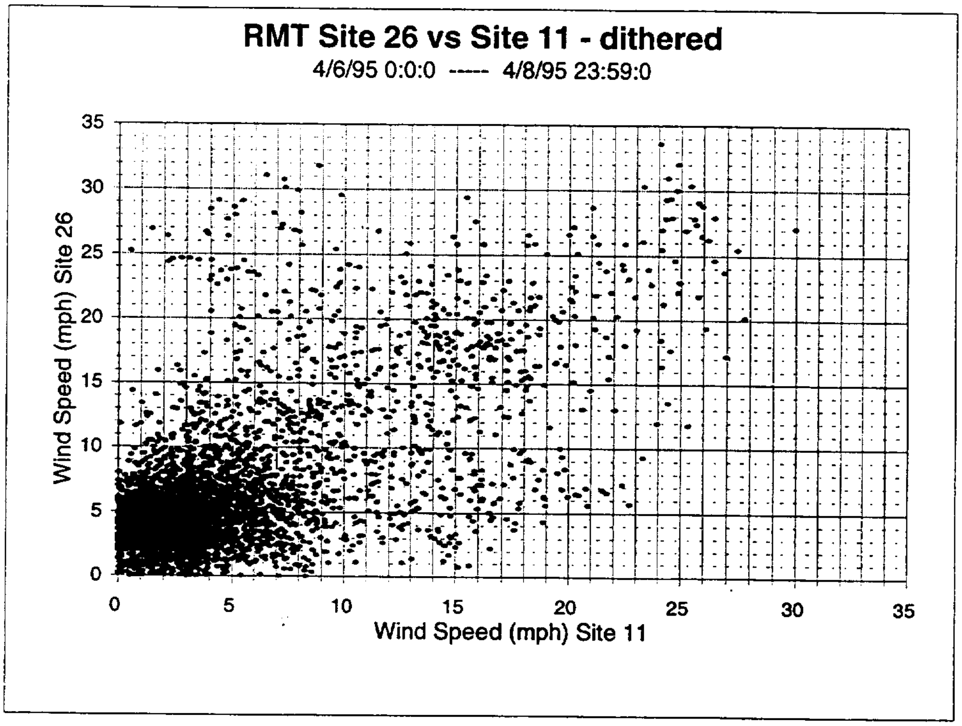

Figure 15. Correlation of Wind Speed Data from Sites 11 and 26

Conclusions

Some of the weather data may be used in a general sense as a mediating variable when examining the relationship of INM computed and ANOMS measured aircraft sound levels. For example, pressure and temperature data may be examined for statistical effects on the sound levels measured.

Though wind speed data available for each event is unlikely to be of much use, wind speed and direction trends may still be valuable. Figures 16 and 17 show data from RMTs 18 and 26, respectively, for the same time period as that shown for RMT 11 in Figure 12. There are clearly trends in general speed and direction, as might be expected, from site to site. Examination of figures such as these could be used to identify time periods of high wind, low wind and the general wind direction, for use in analyzing computed *versus* measured levels. For example, these data could identify times of high wind when operations could be excluded from analysis. Or, propagation effects might be examined by focusing on specific operations, RMTs and wind directions.

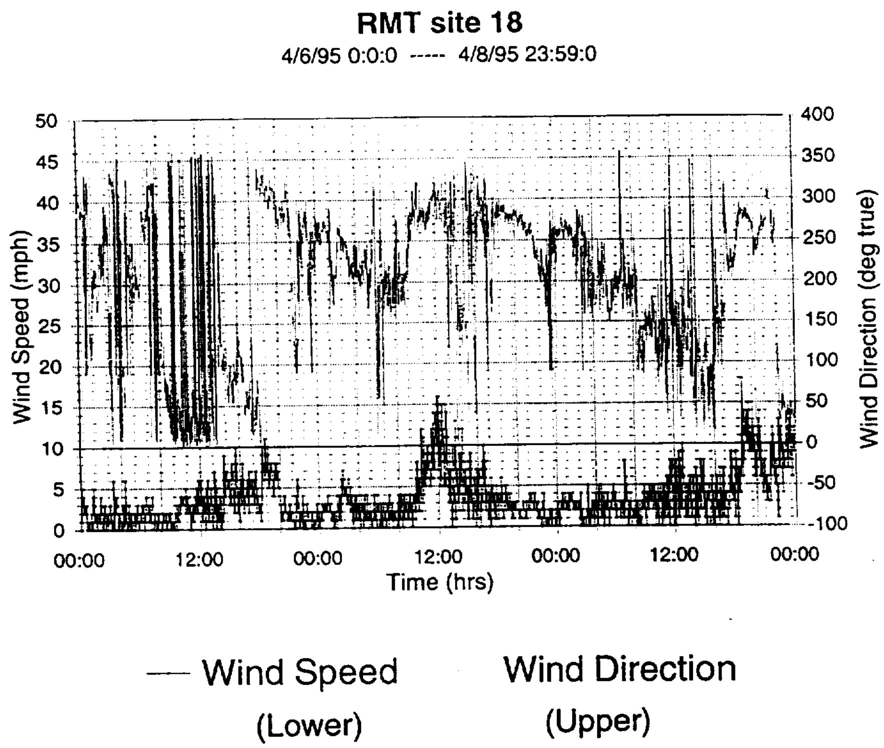

Figure 16. Wind Speed and Direction Data - RMT 18

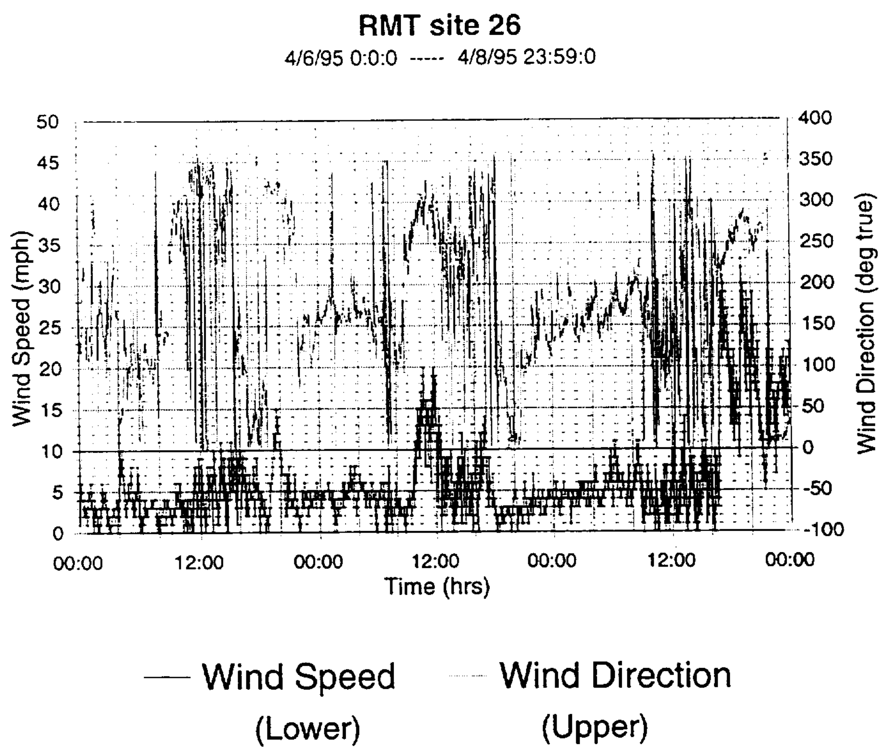

Figure 17. Wind Speed and Direction Data - RMT 26

4.2 Cleaning of Measured Data

ANOMS contains a series of algorithms to identify noise events, then to associate each noise event with an aircraft operation. The algorithms and the parameters used have been checked and in general work well. Detailed examination of the airspace and sound level time histories of 7 departures and 20 arrivals showed that errors can occur, such as inclusion of more than one aircraft operation in a noise event, or too little of the time history being included to accurately measure an SEL. Hence, some incorrectly measured SEL are to be expected, and various approaches were examined to determine if any additional logical criteria could be used to eliminate or reduce outliers or erroneously measured events.

4.2.1 Maximum A-Weighted Level and Duration of Measurement

Such criteria as maximum level or duration of the noise event were tried and tended to discard large numbers of operations from the data base (30% to 50%), but had little effect on the overall distribution of data, as well as having little justification for their use across all operations. For example, because ANOMS uses a dynamic threshold, dependent upon the ambient sound levels, use of a minimum acceptable L_{max} can eliminate valid events.

Also, ANOMS can accurately detect and measure aircraft at a considerable distance from an RMT. Figure 18 is a noise event time history associated with Delta 914 departure, as measured at RMT 22. Figure 19 shows the airspace at 12:42:06, the time of the start of the event. DAL 914 is shown proceeding along its flight track toward the northwest. RMT 22 is the point displaying "52", the sound level it is measuring at that moment. Figures 20 and 21 show the aircraft's location at the time of a maximum (12:42:55, level at RMT 22 = 71) and at the end of the event (12:43:50, level at RMT 22 = 53). The airspace and the time history show reasonable agreement in terms of aircraft location and sound level. Additionally, there are no nearby flights likely to influence the measured levels. This event and associated operation seem reasonably measured and matched.

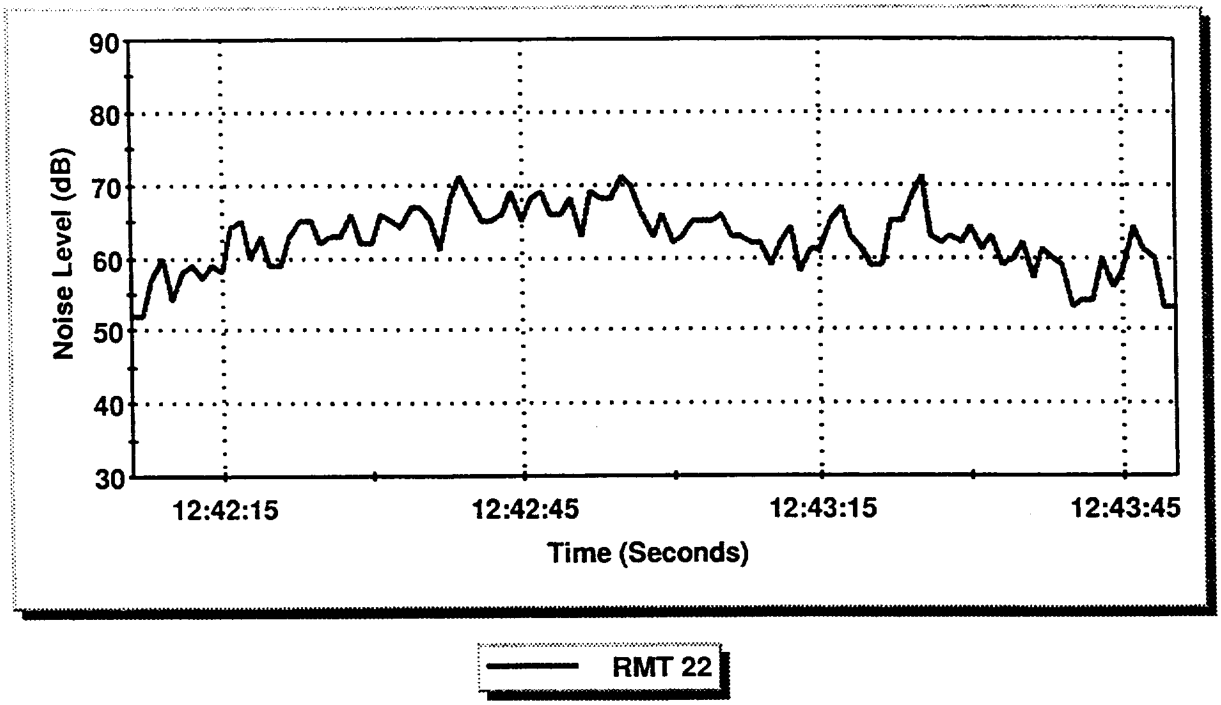

Figure 18. DAL 914 Departure Noise Event Measured by ANOMS

Table 5 presents values of various parameters for DAL 914 as determined at RMT 22. Note that the slant distance is over 10,000 feet, as computed by ANOMS. The INM slant distance is different due to the INM profile placing this aircraft at a lower altitude than it actually was at this location. (The difference between ANOMS and INM range - the perpendicular distance between the ground track and the RMT - is only 128 feet, less than a 2% error.) For these types of slant distances, durations can be quite long, here 105 seconds, so that use of a general maximum or minimum duration to attempt to eliminate erroneous events was also tried and judged as too arbitrary, and too likely to exclude valid events.

Table 5. DAL 914 Departure Parameter Values for RMT 22

Flight Number	SEL (dB)		Slant Distance, ft		Altitude, ft		Event Duration, sec	Speed, INM, kts
	ANOMS	INM	ANOMS	INM	ANOMS	INM		
DAL 914	84.5	74.0	10645	9362	8707	7190	105	309.4

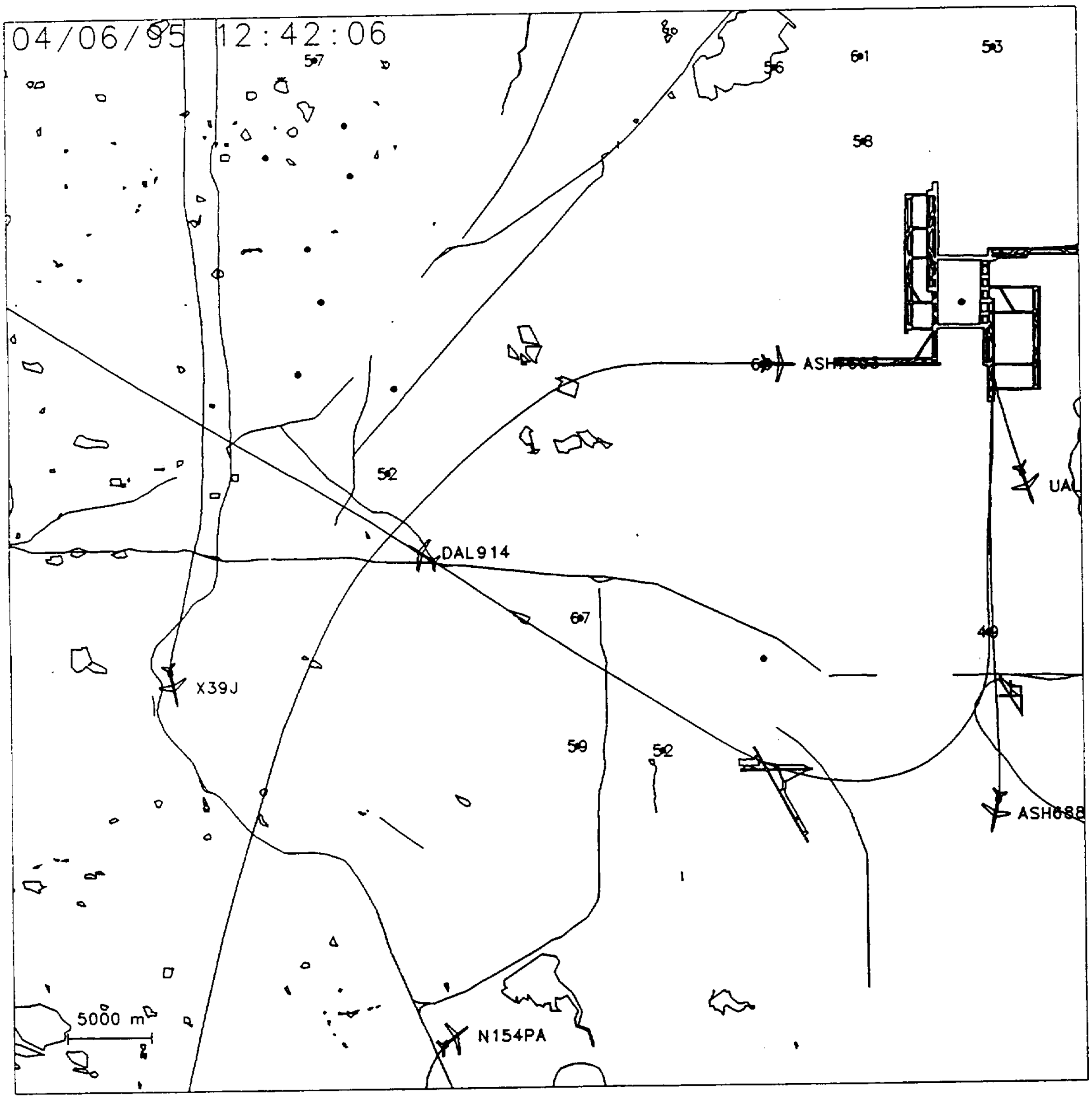

Figure 19. DAL 914 Departure Track - Event Start

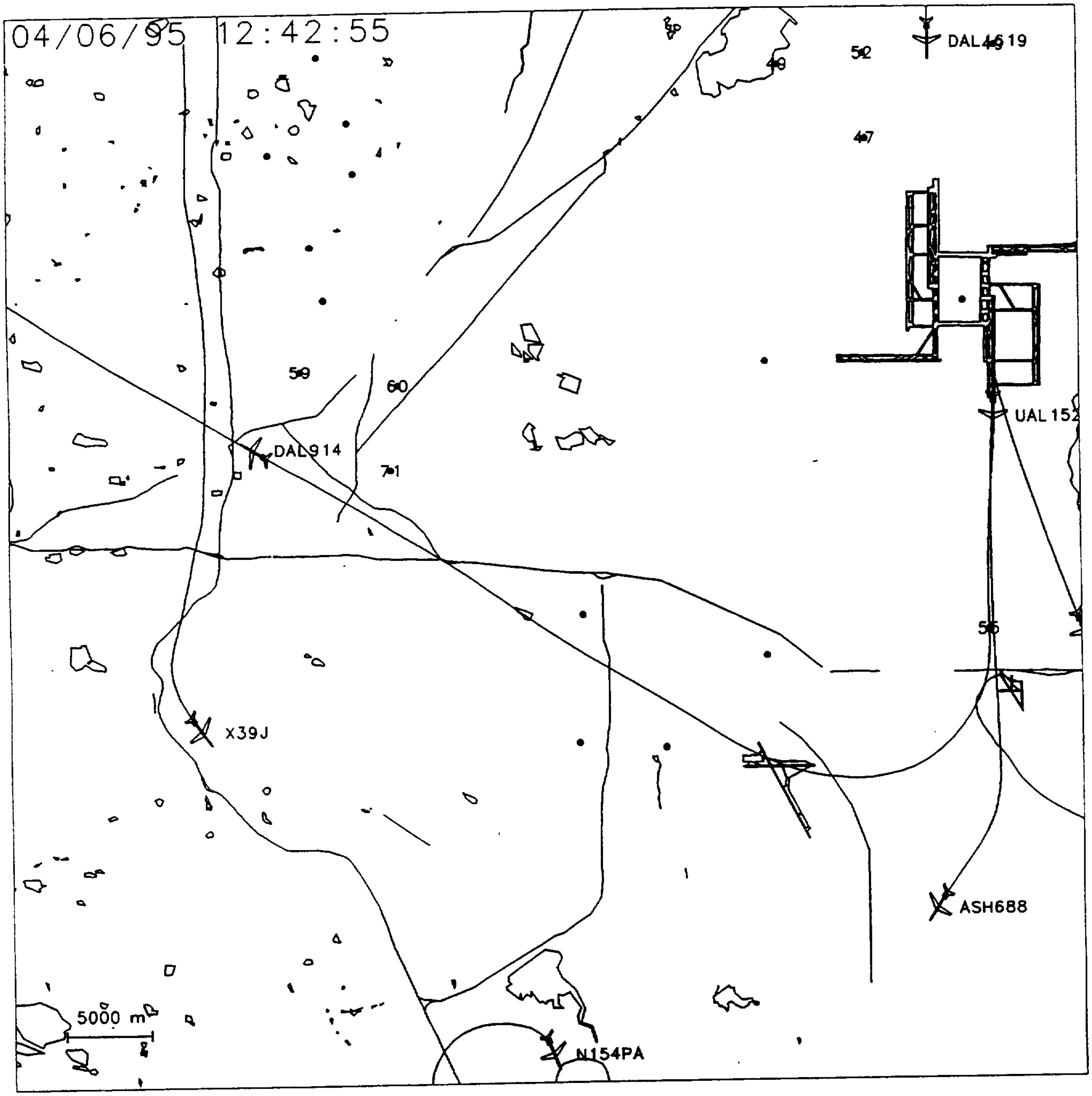

Figure 20. DAL 914 Departure Track - First Maximum

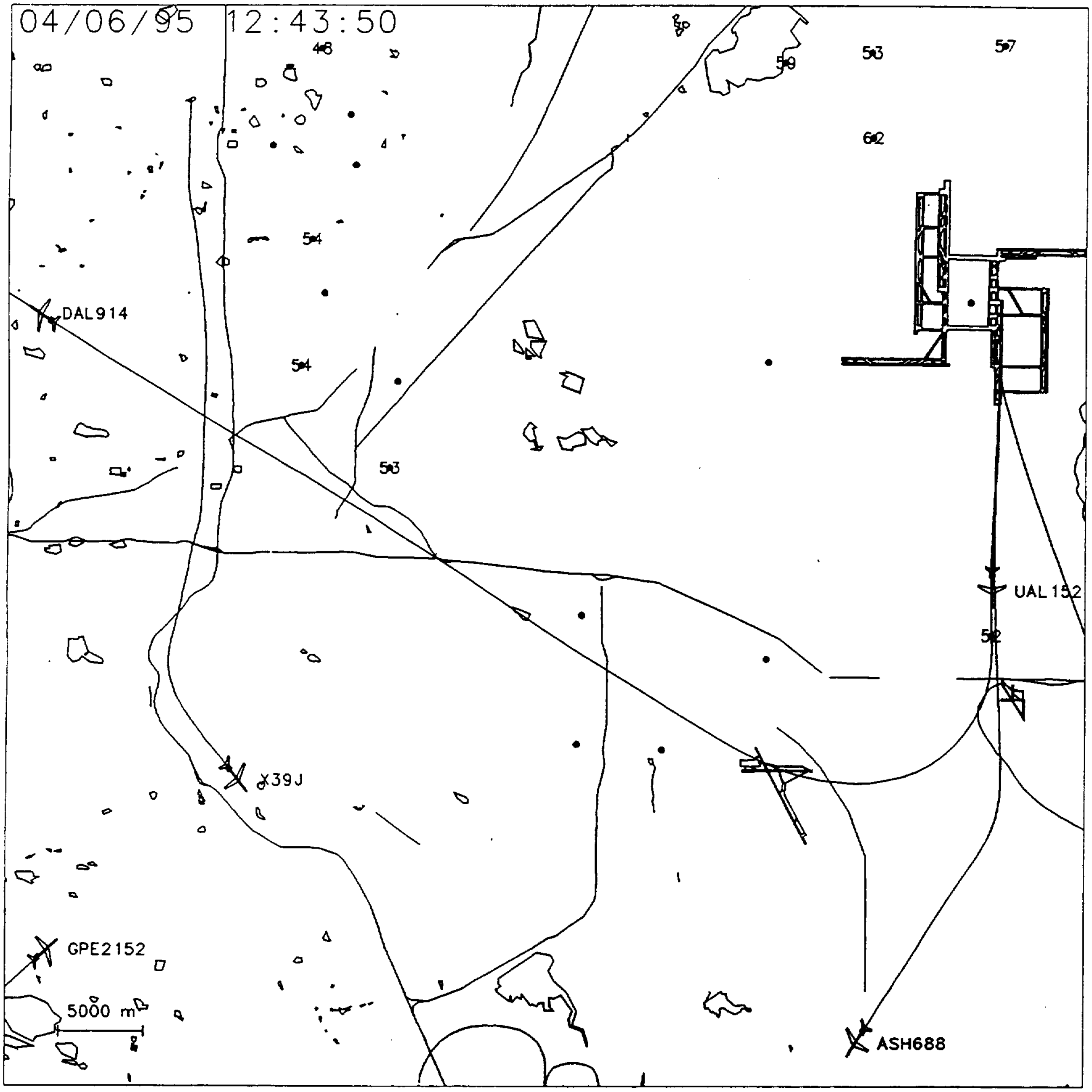

Figure 21. DAL 914 Departure Track - Event End

4.2.2 Elevation Angle

Elevation angle, or the angle of the aircraft above the horizon relative to the RMT, at the point of closest approach (PCA), was considered as a means for sorting the data. Figure 22 shows all operations, in terms of "Difference in SEL" *versus* elevation angle for the six aircraft types being analyzed. (Table 4 shows slightly higher total data points because a small number of points with erroneous INM calculations were eliminated for the figure). "Difference in SEL" or "Difference" will be the term used to denote the result of subtracting the measured SEL from the INM calculated SEL. This Difference is greater than zero when the INM computed level is higher than the measured level. Because Figure 22 does not clearly show the density of data by elevation angle, Figure 23 is provided, giving number of data points by five degree increments.

Figure 22 shows a wide distribution of the data and, at least for angles greater than 10 degrees, no clear dependance or bias of Difference as a function of elevation angle. In general, it is deemed reasonable to analyze any and all data above 10 degrees. However, INM calculations of SEL for flights below 60 degrees are affected by excess attenuation caused by the influence of the ground. In the initial analyses conducted here, only data for flights at or above 60 degrees elevation angle will be used. By selecting only these data, any potential complexities produced by modeled over-ground propagation need not be considered.

Only data points above 60 degrees elevation angle will be used for the analysis.

4.2.3 Slant Distance

Figures 24 and 25 provide similar plots of the data, but with respect to the ANOMS computed slant distance. Two peculiarities are worth describing. First, the series of vertical lines of data points beyond slant distances of about 7000 feet are due to operations at very low elevation angles. Figure 22 also shows these same vertical lines of data points, but they all occur below 10 degrees elevation angle. Several of the operations that produced the significant negative Difference (measurement much higher than computed value) were examined in detail. These were arrivals to runway 16, passing by RMT 2 at about 7000 feet PCA distance (see Figure 2). There appeared to be no error in the measurement, suggesting that cases occur where long distance propagation is significantly better than that contained in INM algorithms. Hence, these data could be useful for eventually exploring long distance propagation at low angles of elevation above the ground. This INM presently addresses this type of propagation using limited empirical data (SAE AIR 1751 [7]).

A second noteworthy occurrence is the group of data points at the shortest slant distances (less than about 1000 feet) that is separated from the bulk of the data. These are arrival operations to Runway 07 over RMT 9. RMT 9 is closer to the airport than is any other site, and arrivals fly almost directly over head, see Figure 2. Hence, the slant distances to these operations are shorter than are the slant distances of any other operations.

Data points will be used for the analysis independent of slant distance.

4.2.4 Temperature

Figures 26 and 27 plot the Difference data points by temperature. There appears to be no relation of Difference to temperature. The INM includes algorithms that change aircraft performance and sound level as a function of temperature. Hence, including data points from all temperatures may make possible an analysis of the accuracy of these assumptions.

Data points will be used for the analysis independent of temperature.

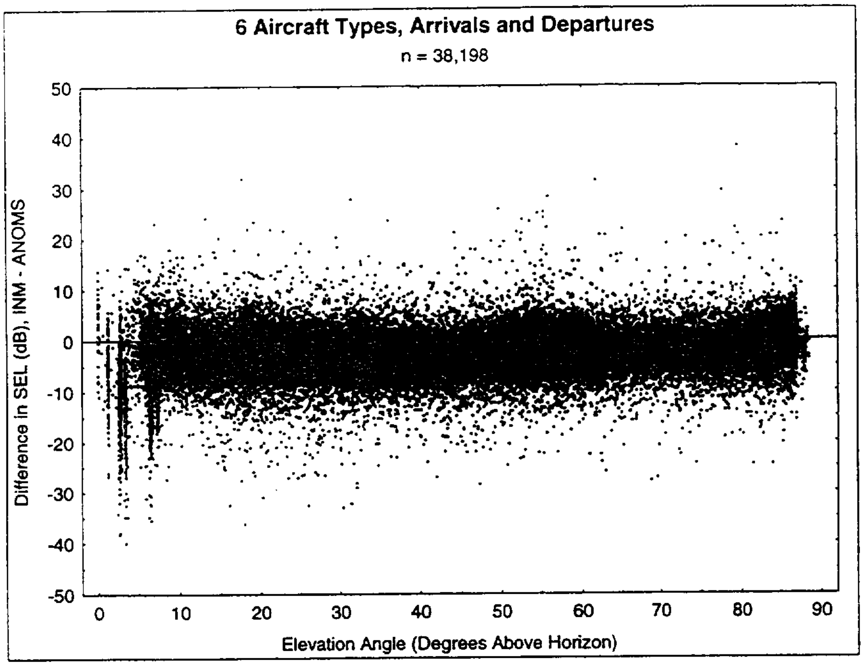

Figure 22. Relation of Difference in SEL (INM-Measured) to Elevation Angle

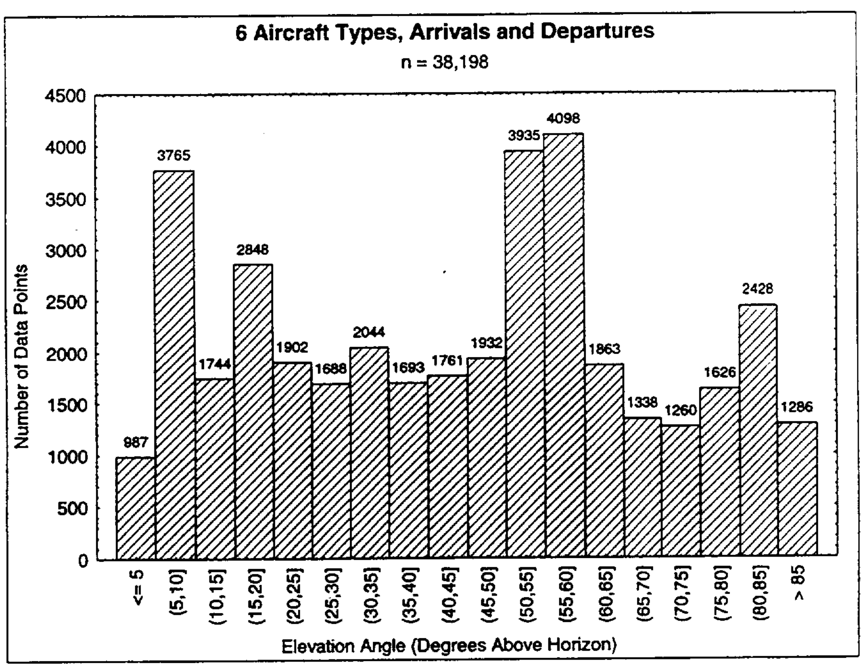

Figure 23. Distribution of Data by Elevation Angle

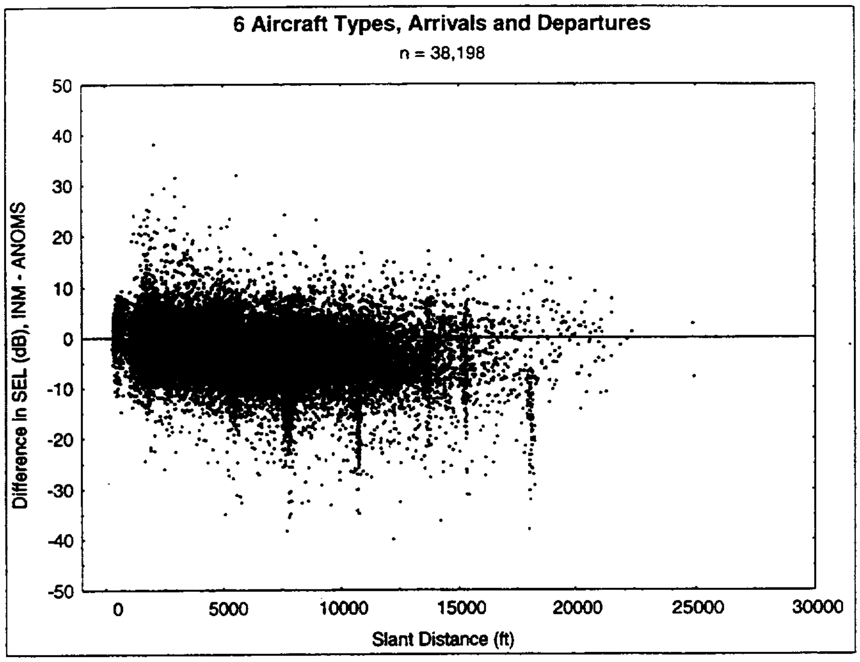

Figure 24. Relation of Difference in SEL to Slant Distance

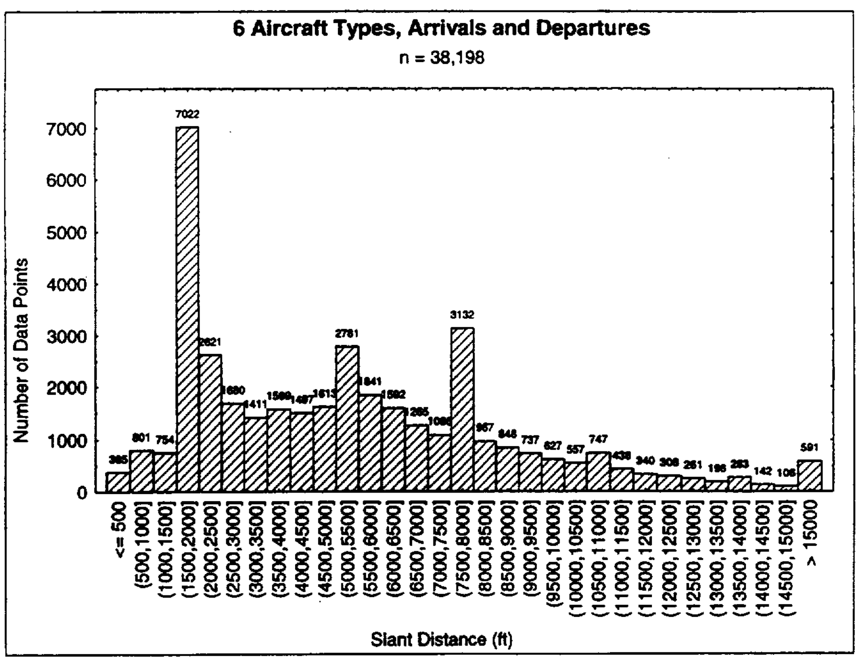

Figure 25. Distribution of Data by Slant Distance

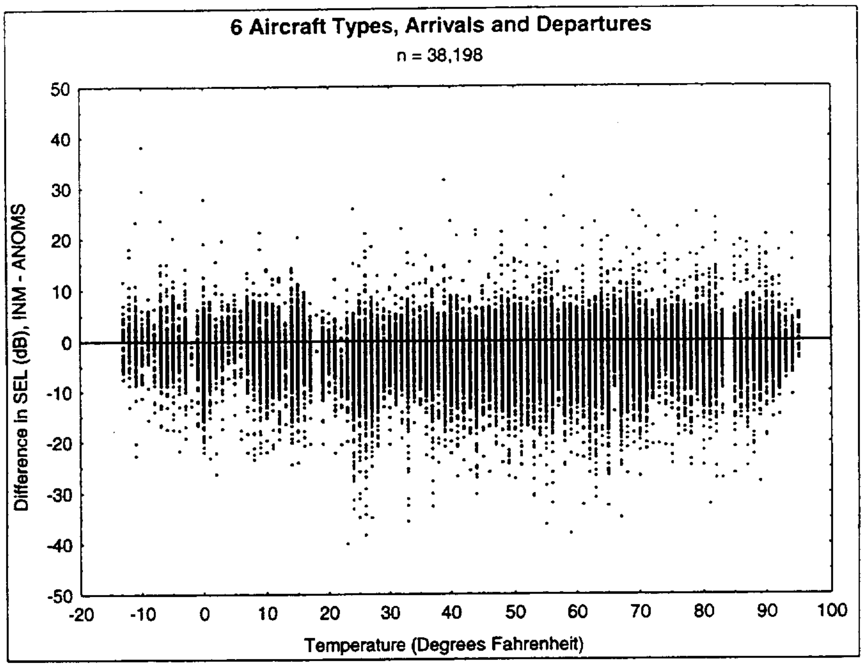

Figure 26. Relation of Difference in SEL to Temperature

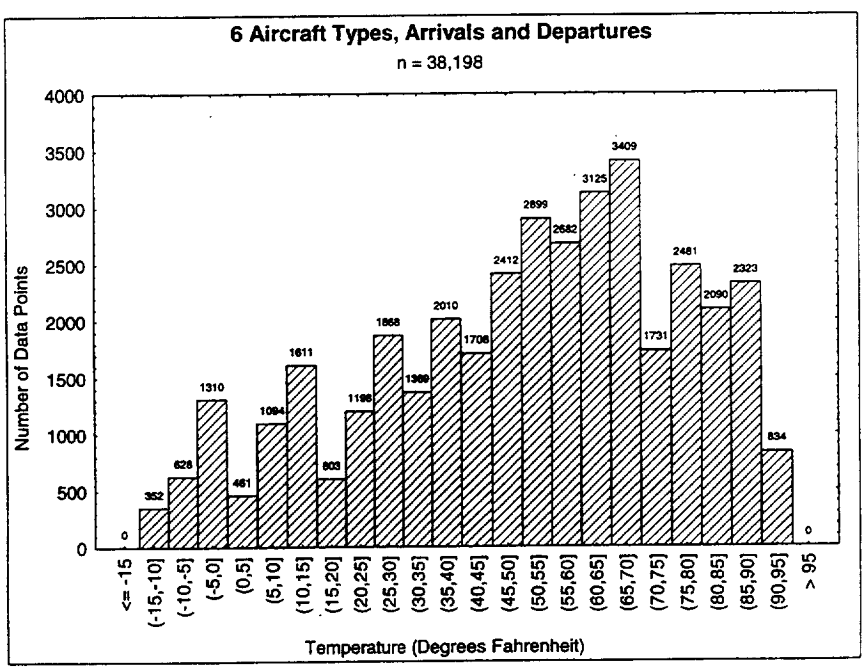

Figure 27. Distribution of Data by Temperature

4.2.5 Wind Speed

Figures 28 and 29 show data distributions by wind speed. As discussed in section 4.1.2, wind speeds are measured at only three of the RMT's and are applied to events measured at all other monitors. Thus wind speed at all other sites is considered only an estimate. However, Figures 12, 16 and 17 show some correlation of wind speed in that higher speeds at one monitor indicate higher speeds at the others. Hence, though exact wind speeds cannot be known, wind speed can be used to filter out data measured when wind speeds may have been high. Since wind gusts or higher wind speeds are known to produce sound levels at monitors that can be miss-identified as an aircraft produced event, wind speed will be used to remove data points. The wind speed of 10 mph was used to eliminate data. Figure 29 shows that some 971 data points will be eliminated.

Only data points having wind speeds less than 10 mph will be used in the analysis.

4.2.6 Selected Filters, Resulting Data and Trends

Applying the selected filters - elevation angles greater than 60 degrees, wind speeds less than 10 mph - the figures of Appendix A result. Figures 30 and 31 are typical of Appendix A and repeat the plots for B727 arrivals, Figures A1 and A2. Figure 30 plots calculated SEL *versus* measured SEL, while Figure 31 plots Difference in SEL (INM SEL minus ANOMS SEL) as a function of distance along the flight track to the PCA. In Figure 30, a point lies on the diagonal when calculated and measured SEL are identical; when calculated exceeds measured, the point lies above the diagonal, and when measured exceeds calculated, the point is below the diagonal. Similarly, data above the diagonal in Figure 30 are greater than zero in Figure 31. Appendix A figures are presented by aircraft type, with arrivals followed by departures.

In Figure 30, the arrival data appear, at the louder SEL values, in horizontal bands. This distribution results because the arrivals are all flying virtually on centerline and passing at the same distance from the RMT's that are not too distant from the airport; hence, the INM computes the same SEL for every such arrival. At the lower SEL (more distant), the SEL values shown are from many different monitors at many distances from arrivals as they turn toward the airport and align with the various runways. Figure 31 displays a similar distribution of data points. Monitors close to the airport / arrival runway are at specific track distances from touch down, and hence all data from one of these monitors line up vertically.

These two figures suggest a trend in the differences between calculated and measured arrival levels. From louder to quieter SEL or from close-in to longer track distances, the distribution of points appears to go from at or above the line of equality to increasingly below this line. In other words, the Difference seems to vary, depending on track distance, becoming increasingly negative with increasing track distance. All of the arrival data display a similar trend, see Figures A6, A10, A14, A18 and A22.

Departure SEL show somewhat different patterns for the Difference, see Appendix A. For example, B727 departures, Figures A3 and A4, show less of a trend from shorter to longer track distances, as do all the other departure data, with a trend for the Difference in SEL varying less with track distance.

To make quantitative progress in understanding differences between calculated and measured SEL, a method is needed to quantify the Difference. One way to quantify these varying degrees of Difference in SEL is to do so as a function of track distance. The next section, Section 4.3, describes and then applies such a method.

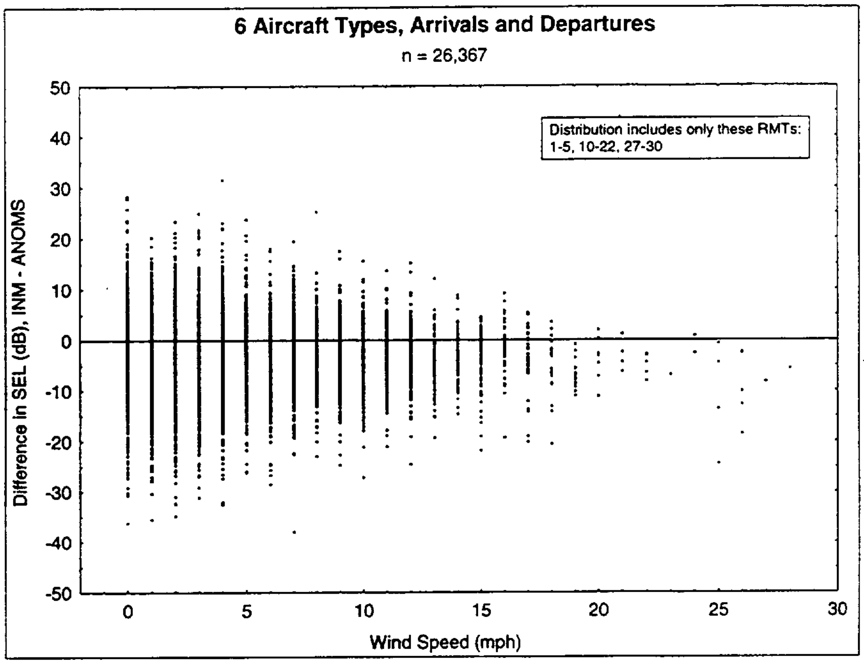

Figure 28. Relation of Difference in SEL to Wind Speed

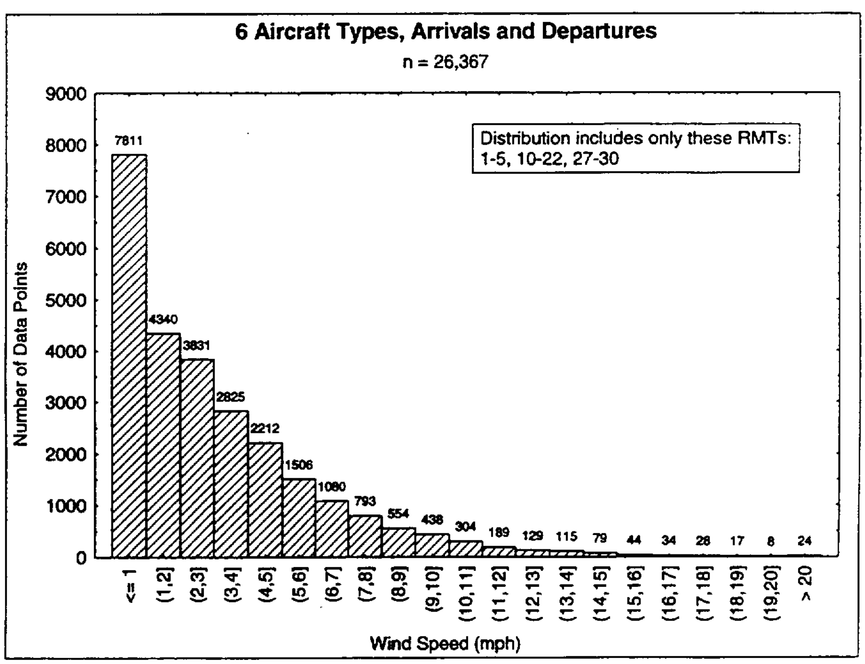

Figure 29. Distribution of Data by Wind Speed

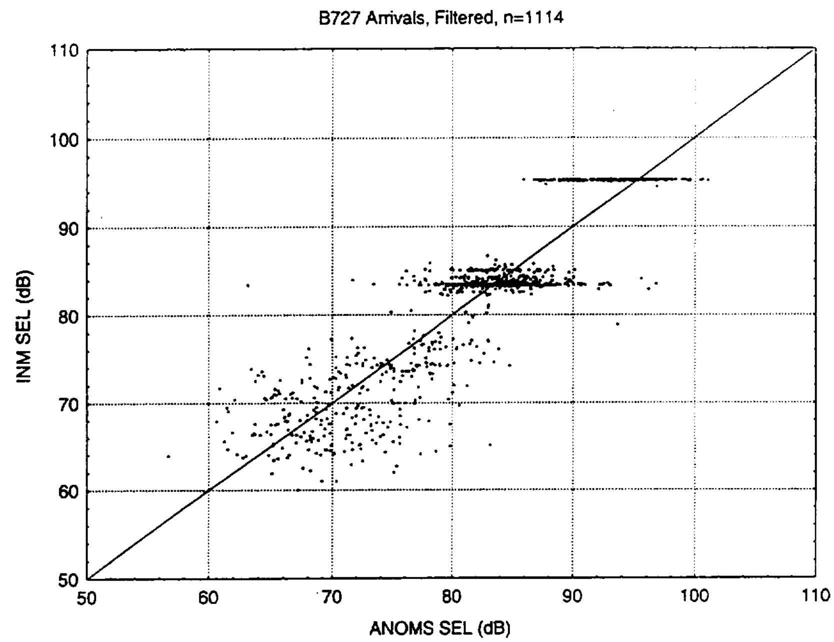

Figure 30. Calculated *versus* Measured SEL, B727 Arrivals

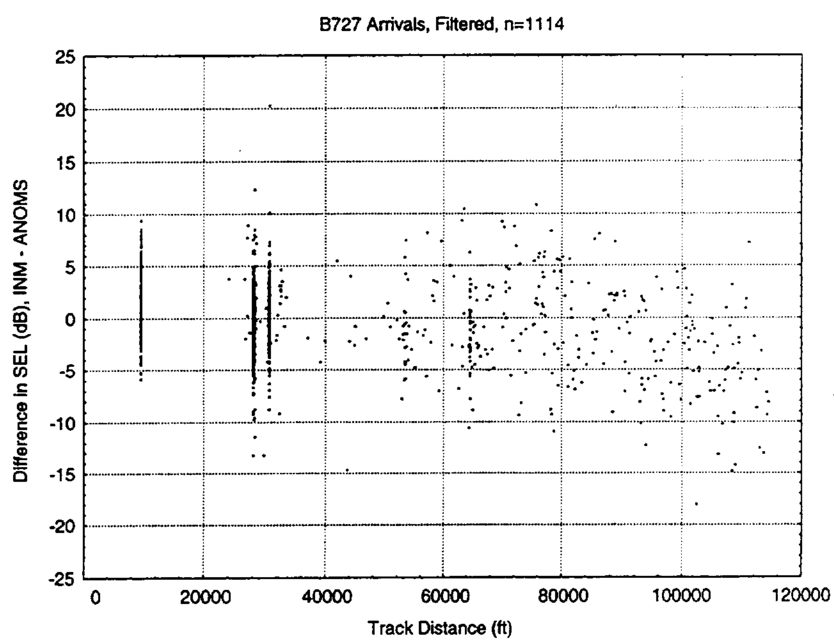

Figure 31. Difference in SEL *versus* Track Distance, B727 Arrivals

4.3 Figures of Merit

4.3.1 Introduction

Figures of merit are intended to be simple, one number measures of how well calculated and measured SEL agree. The primary features of the figures of merit developed in this analysis are that they:

1) quantify the difference between calculated and measured SEL for each specific aircraft type, by arrival and departure,

2) relate to the way the INM models aircraft flight,

3) relate to the calculation of Day-Night Average Sound Level, DNL,

4.3.2 Importance of Track Distance

As Figures 30 and 31 and the figures of Appendix A show, calculated and measured SEL values differ by varying amounts, depending upon aircraft type, operation type (arrival or departure) and by track distance. Because INM calculations depend upon flight procedures that are modeled as a function of location along the flight track, it is reasonable to expect that analysis of Differences will be most productive, and make the most inherent sense, if done as a function of track distance.

For example, Figure 31 shows that average Difference in SEL at a track distance of about 10,000 feet appears different from the average Difference at 30,000 feet track distance. Average Difference in SEL at 10,000 feet looks to be roughly 1 to 2 dB, while at 30,000 feet it might be 0 to -1 dB (though without using the complete distribution, averages cannot be determined). Reasons could be that: 1) aircraft are modeled lower, slower and/or using more thrust at 10,000 feet than they actually do; 2) aircraft actually fly lower, slower, or use more thrust at 30,000 feet than modeled. The INM essentially describes how an aircraft is flown by a series of steps (with changes in thrust, rate of climb, etc.) along the track flown by the aircraft. Hence, track distance is a convenient and relevant means to separate the effects and causes of Difference in SEL because track distance relates to how the INM models flight procedures. The method chosen is to examine Difference in SEL for specific track distance intervals, for each aircraft type and operation type.

4.3.3 Use of Energy Average Differences

The figure of merit should quantify how much the INM calculated SEL and the measured SEL differ on average. The goal, ultimately, is to insure that the INM produces accurate values for noise exposure in terms of DNL, Day-Night Average Sound Level. Consequently, it is important that Difference in SEL be analyzed in a way that will improve the calculation of DNL. DNL at a given point on the ground is calculated by summing on an energy basis the SEL values produced by an aircraft flying over or near that point on the ground. Hence, Difference in SEL should be determined and analyzed on the basis of how the energy sum of all INM calculated SEL compares with the energy sum of all measured SEL. The approach used here is to determine, for a specific aircraft type, operation and track distance interval, the difference in the energy average calculated and energy average measured SEL. This difference is the figure of merit for that specific aircraft / operation / track distance interval. Confidence limits, at the 95 % level, are also calculated for each figure of merit.

4.3.4 Selection of Track Distance Intervals

A first step in the development of the figures of merit is selection of track distance intervals for which the figures of merit will be computed. Figure 31 suggests, simply by the distribution of the data, what the intervals could be for B727 arrivals - less than 20,000 feet, 20,000 to 40,000 feet, over 40,000. Also, however, altitude information as a function of track distance was examined and compared with standard INM altitude profiles. Appendix B contains altitude plots for each aircraft type and operation. Best fit altitude profiles were derived for each set of data and then compared with comparable INM profiles. Differences between best fit and INM altitude profiles were also considered in selecting track distance intervals.

Figures 32 through 36 repeat Figures Be through B5. Figure 32 plots all B727 arrival altitudes (ANOMS altitudes) by track distance. Each point presents the altitude (from the radar data) at the point of closest approach, PCA. (Points with altitudes between 5000 and 6000 feet at track distances less than 50000 feet are erroneous and were removed from further analysis. [8]) The least squares fit to these points is shown as is the standard INM 3 degree approach profile. Figure 31 suggested that the data be analyzed for track distances of 0 - 20,000 feet, 20,000 to 40,000 feet, and over 40,000 feet. Figure 32 shows that profiles agree well to 40,000 feet and differ at over 40,000 feet. In other words, the altitude data support the division at 40,000 feet.

Figures 33 through 36 provide departure altitude information. Figure 33 presents the data points, identified by departure stage length. Figure 34 plots the least squares fit profiles for each stage length, and Figure 35 shows the 95 % confidence limits for each of the stage lengths. Finally, Figure 36 gives a representative INM 727 set of departure profiles. Comparing Figures 35 and 36, INM profiles agree reasonably with the least squares profiles out to between 40,000 and 80,000 feet. Considering the distribution of data shown in Figure A4, 60,000 feet was chosen as a dividing point for analysis of B727 departures. In a similar manner, the arrival and departure altitude profiles of the other five aircraft types were examined and Table 6 gives the track distance intervals selected for analysis of each aircraft type and operation.

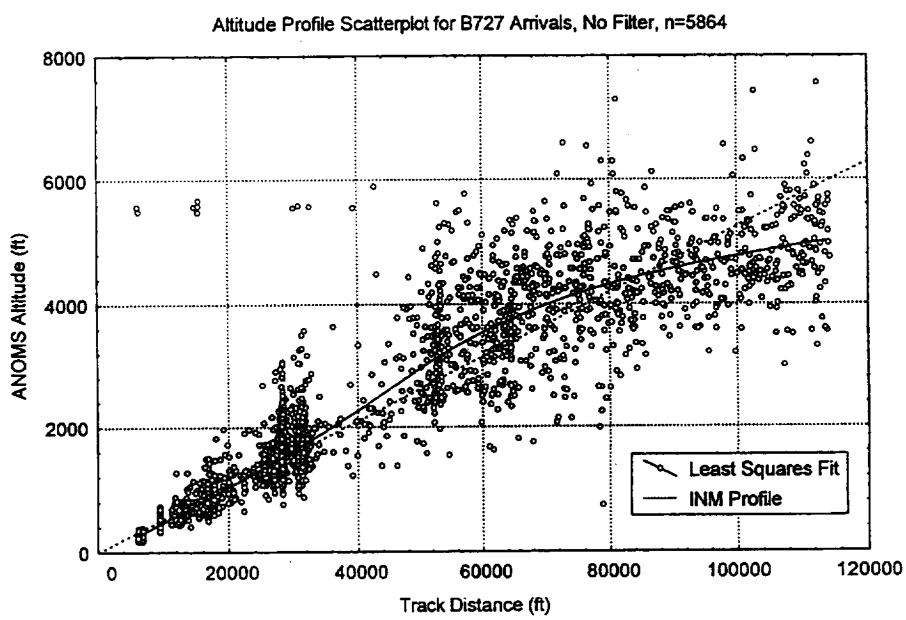

Figure 32. Altitude *versus* Track Distance, B727 Arrivals

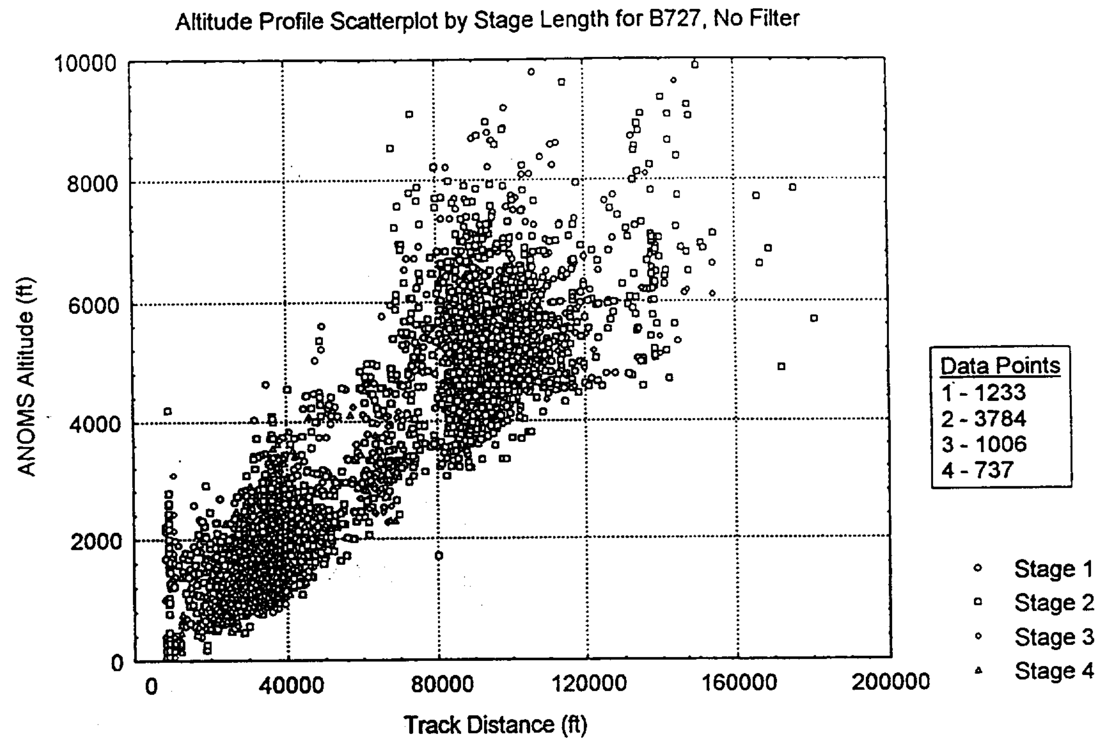

Figure 33. Altitude *versus* Track Distance, B727 Departures

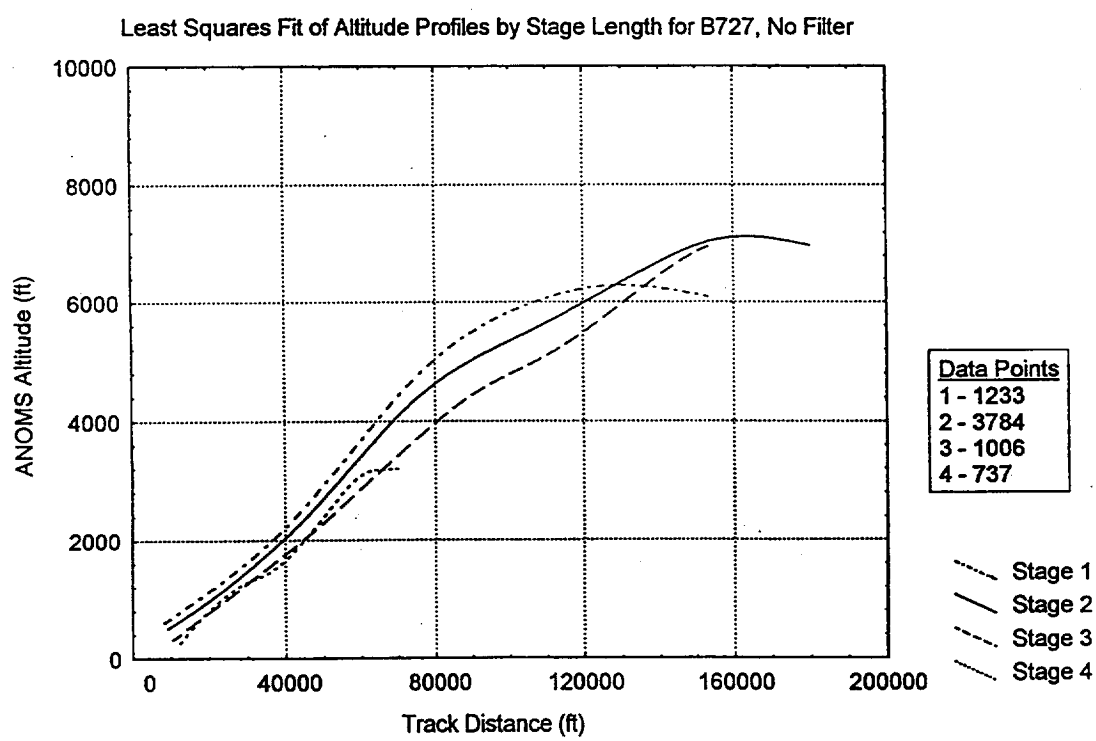

Figure 34. Least Squares Fit Altitude Profiles, B727 Departures

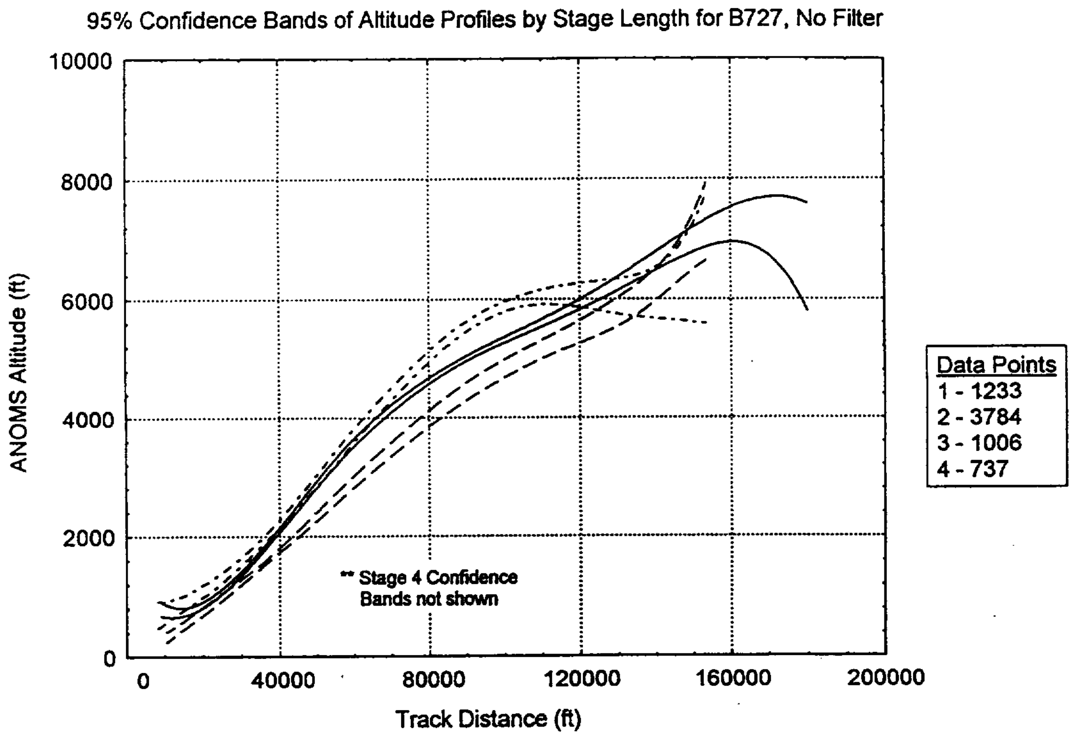

Figure 35. 95% Confidence Limits on Altitude Profiles, B727 Departures

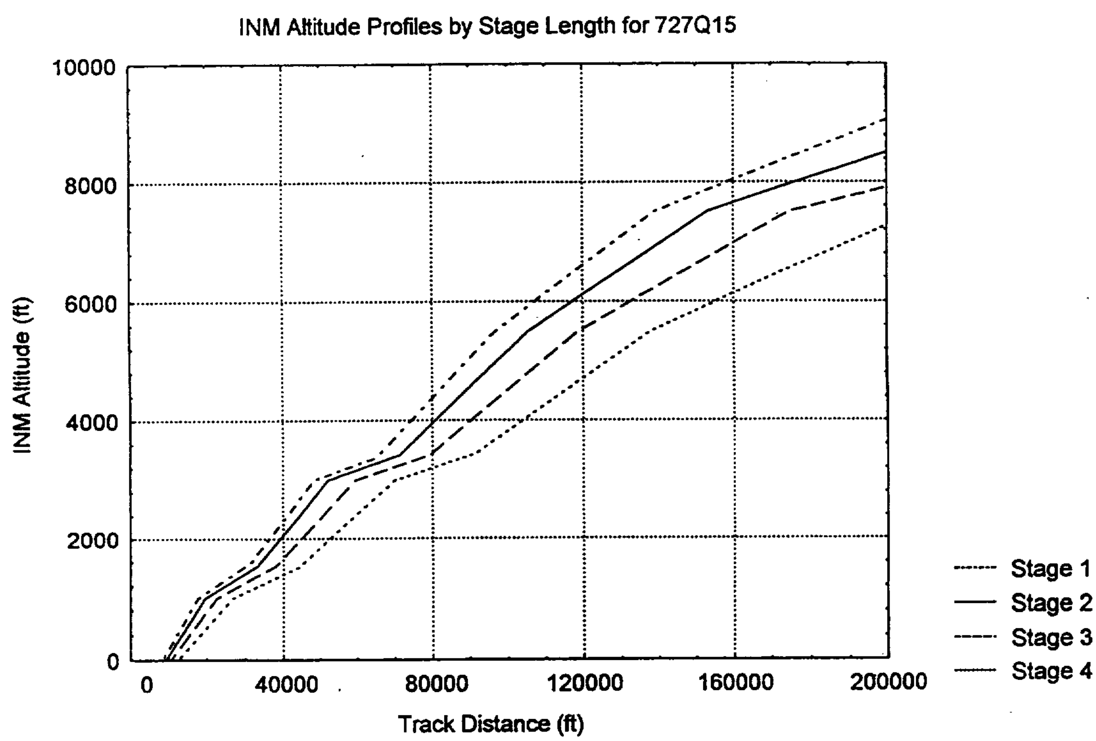

Figure 36. Representative INM Altitude Profiles, B727 Departures

Table 6. Track Intervals Selected for Analysis

Aircraft Type	Operation	Track Intervals (feet)
B727	Arr	0 - 20,000 20,000 - 40,000 > 40,000
	Dep	0 - 60,000 > 60,000
B733	Arr	0 - 20,000 20,000 - 40,000 > 40,000
	Dep	0 - 30,000 30,000 - 50,000 > 50,000
B73S	Arr	0 - 20,000 20,000 - 40,000 > 40,000
	Dep	0 - 60,000 > 60,000
B757	Arr	0 - 20,000 20,000 - 40,000 > 40,000
	Dep	0 - 50,000 > 50,000
DC10	Arr	0 - 20,000 20,000 - 40,000 > 40,000
	Dep	0 - 60,000 > 60,000
MD80	Arr	0 - 20,000 20,000 - 40,000 > 40,000
	Dep	0 - 60,000 > 60,000

The figures of Appendix B suggest two noteworthy observations that have relevance to modeling of aircraft operations. First, all the arrival altitude data suggest a similar approach procedure for all aircraft: at Denver, aircraft tend to intercept and overfly the 3 degree glide slope at 60,000 to 90,000 feet (10 to 15 NM), then converge onto this glide slope from above at 20,000 to 40,000 feet from touch-down. Second, stage length does correlate, though not uniformly, with climb profile: the shorter the stage length (lower the stage length number), the steeper the climb-out.[4]

4.3.5 Resulting Figures of Merit

As discussed, the figures of merit are based on energy average differences between calculated and measured SEL. It is important to distinguish between an arithmetic average and an energy average. When determining an arithmetic average of sound levels (decibels), outliers (assuming they are not too extreme) do not strongly influence the average. Energy averages, on the other hand, are very strongly influenced by outliers on the higher side. So much energy is represented by only a 10 dB difference, that a few unusually loud samples can far outweigh the effects of many lower levels. Figure 37 shows the B727 arrivals for track distances over 40,000 feet, (see also Figures 30 and 31). The dashed line passes through the arithmetic average of both the INM calculated and ANOMS measured SEL - a vertical displacement in this case of -1.65 dB. In other words, on an arithmetic average basis, calculated SEL for these arrivals are 1.65 dB lower than measured SEL; increasing all calculated levels by 1.65 dB would yield identical calculated and measured average levels.

DNL values, however, are not related to the arithmetic average, but to the total sound energy of all flights, and hence to the energy average flight. *Hence, it is the difference between energy average calculated SEL and energy average measured SEL that is important in this analysis.* Figure 38 shows the same arrival data, but with the dashed line labeled "energy average regression" passing through the energy average calculated and measured SEL values. The importance of the high level outliers is evident since they are responsible for pulling the energy regression line down from the equality line.

It seems inappropriate to use the energy average of all the data points because, in many cases a few significantly high outliers may heavily influence the result, particularly when the data are widely scattered. Figure 38 shows that for these data, the INM calculates SEL on an energy average basis about 4 dB lower than the measured SEL (the vertical displacement of the dashed line). A method is needed to reasonably omit outliers. These outliers, particularly at the larger track distances, are likely to result from inaccurate measurements (measurements, for example, that include non-aircraft noise), incorrectly identified aircraft or flight tracks, etc.

One possible method to remove outliers is "Chauvenet's Criterion" which simply stated says to exclude outliers when twice as many measurements are needed before even one of the outliers would be statistically likely to occur. Figure 39 shows the same B727 arrival data, but with Chauvenet's Criterion upper and lower cutoffs shown together with the resulting energy regression. For these data, Chauvenet's Criterion remove only one data point, and it appears to be too limited a cut-off criterion for removing outliers

---

4 The arrival data, such as that of Figure 32, also demonstrate a noteworthy feature of the INM. In these and other arrival data there appear several points that have unbelievably high altitudes of about 5,600 feet, despite being less than 40,000 feet from touch-down where altitudes should be less than 2,000 feet. These points were examined, and it is the fact that the standard INM approach profiles end at 6000 feet AGL that produced this result. The INM did not "see" the part of the track beyond 6000 AGL that looped back and flew over the monitor at a much larger track distance.

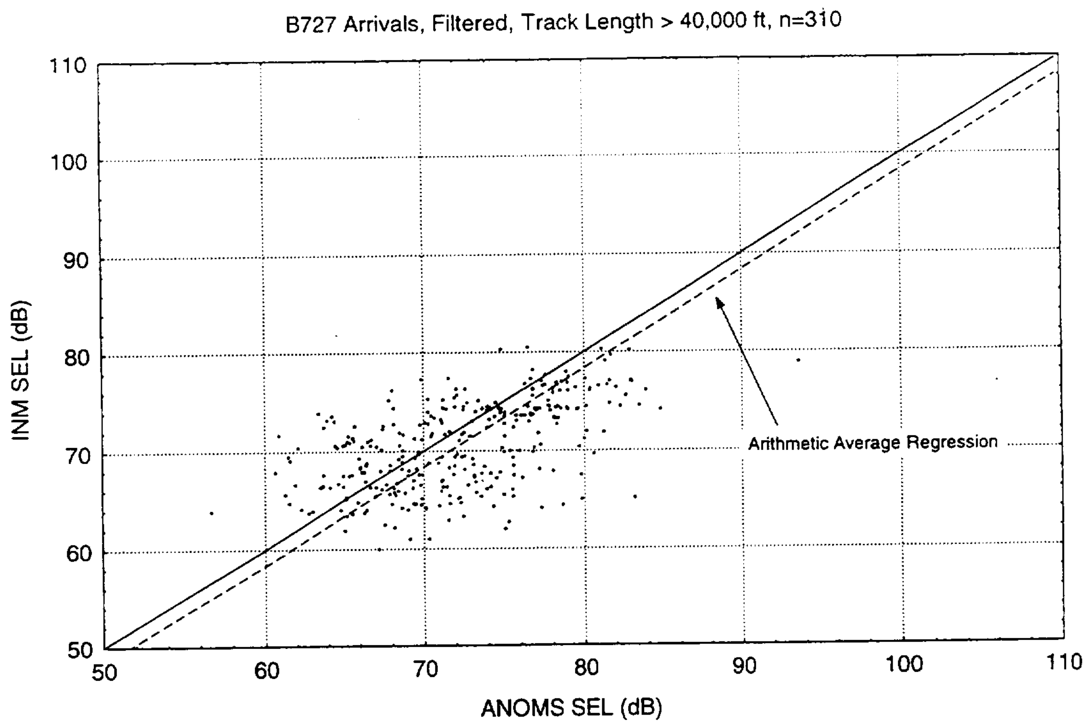

Figure 37. B727 Arrivals and Arithmetic Average Regression

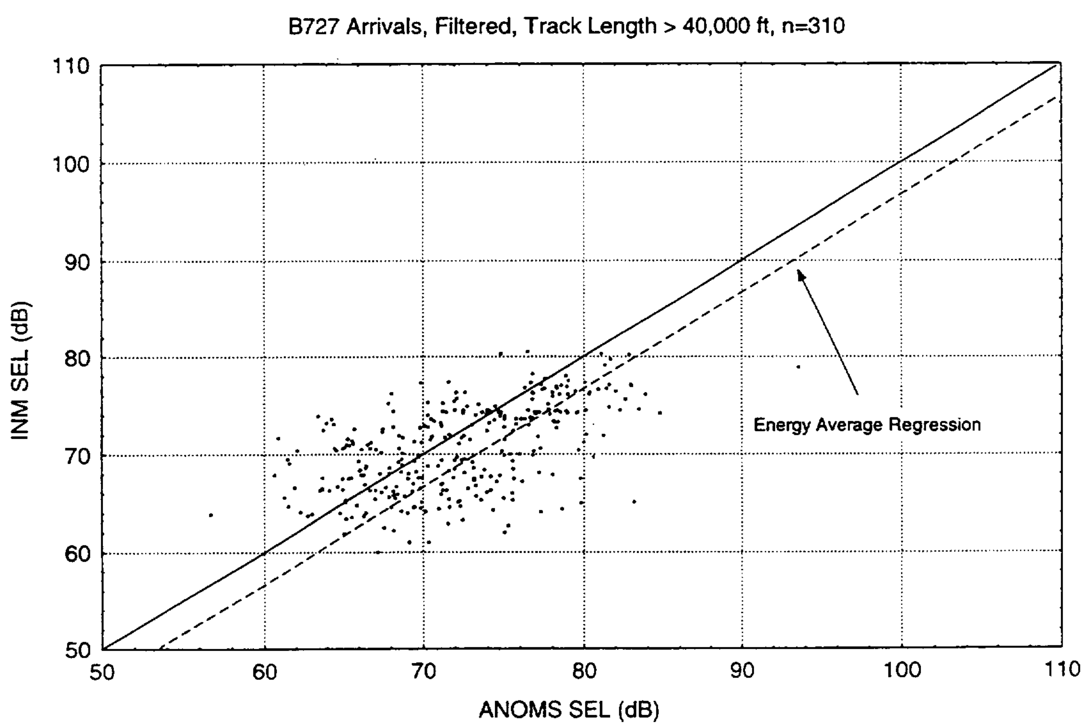

Figure 38. B727 Arrivals and Energy Average Regression

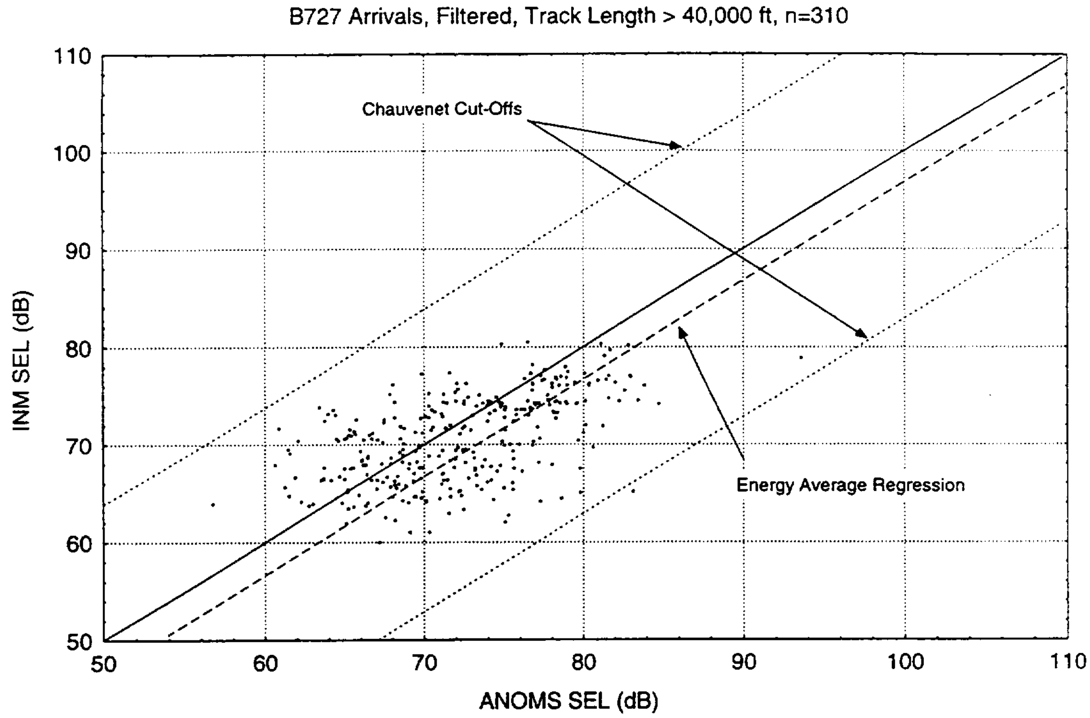

Figure 39. B727 Arrivals and Chauvenet's Criteria to Eliminate Outliers

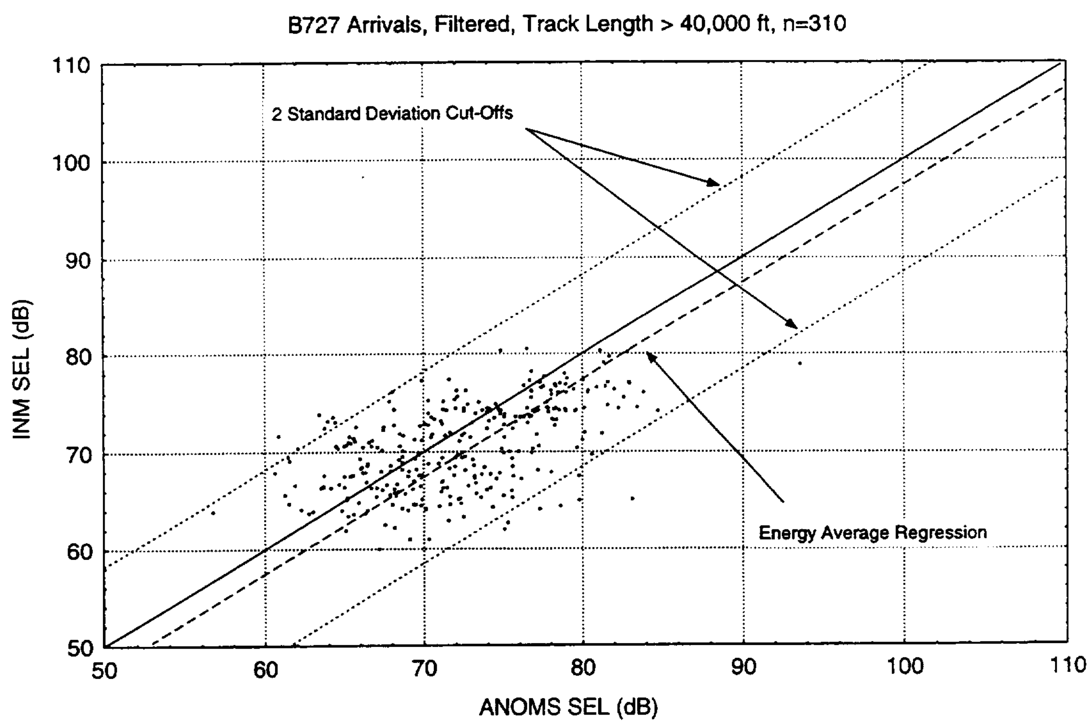

Figure 40. B727 Arrivals and Two Standard Deviations to Eliminate Outliers

Another possible method for removing outliers is to exclude all points outside of two standard deviations. Figure 40 shows the results of such an approach. The energy regression is also shown, and the change of its location from Figure 39 is about 1 dB. In Figure 39, the energy regression is below the equality line by 3.27 dB (the figure of merit), while in Figure 40 it is 2.46 dB below the equality line. In computation of the figures of merit, both methods have been used, and the results presented in Table 7.

Table 7. Figures of Merit Using Two Methods for Excluding Outliers

Aircraft Type	Operation	Track Interval (feet)	Chauvenet		Two Standard Deviations	
			Figure of Merit, dB	95% Confidence Limit, dB	Figure of Merit, dB	95% Confidence Limit, dB
B727	Arr	0 - 20,000	0.91	0.49	1.18	0.43
		20,000 - 40,000	-1.15	0.32	-0.83	0.25
		> 40,000	-3.27	2.17	-2.46	0.91
	Dep	0 - 60,000	-1.30	0.96	-1.49	0.87
		> 60,000	-3.46	0.41	-3.48	0.37
B733	Arr	0 - 20,000	2.39	0.15	2.40	0.13
		20,000 - 40,000	-1.34	0.24	-1.31	0.22
		> 40,000	-3.48	0.49	-3.46	0.46
	Dep	0 - 30,000	-2.52	0.25	-2.56	0.19
		30,000 - 50,000	-3.59	0.30	-3.23	0.22
		> 50,000	-4.74	0.23	-4.52	0.18
B73S	Arr	0 - 20,000	0.91	0.50	1.62	0.33
		20,000 - 40,000	-0.19	0.64	0.51	0.34
		> 40,000	-3.15	0.97	-2.82	0.80
	Dep	0 - 60,000	-1.51	1.25	-2.93	0.68
		> 60,000	-5.38	0.47	-5.26	0.41
B757	Arr	0 - 20,000	0.10	0.96	1.78	0.41
		20,000 - 40,000	-1.77	0.64	-1.27	0.48
		> 40,000	-4.62	1.32	-4.26	1.06
	Dep	0 - 50,000	-1.65	0.63	-2.17	0.40
		> 50,000	-5.15	0.35	-5.15	0.35
DC10	Arr	0 - 20,000	1.69	0.48	1.69	0.48
		20,000 - 40,000	-1.42	0.61	-1.54	0.56
		> 40,000	-9.23	1.16	-9.25	1.10
	Dep	0 - 60,000	2.25	0.48	2.25	0.45
		> 60,000	1.09	0.52	1.16	0.45
MD80	Arr	0 - 20,000	-0.95	0.47	-0.88	0.43
		20,000 - 40,000	-4.43	0.40	-4.31	0.34
		> 40,000	-7.93	2.23	-7.93	2.23
	Dep	0 - 60,000	0.15	0.67	-0.11	0.58
		> 60,000	-1.46	1.61	-0.92	1.05

These figures of merit are best understood by considering them in comparison with the figures of Appendix A. One way to think of a figure of merit is to consider that if every calculated level were adjusted by the figure of merit, then the energy mean SEL of the calculated values would equal the energy mean SEL of the measured values for the data used; it is, in effect, a gross adjustment that would make calculations "agree" with measurements. (Such an adjustment would also make calculated DNL agree with measured DNL.)

For example, the figures of merit for B727 arrivals should be compared with Figure B2 or Figure 31. The Chauvenet method figure of merit of 0.91 dB, when compared with the line of data between 0 and 20,000 feet, seems reasonable, if all data points are considered. Table 8 lists the high and low cutoffs that result from the two methods for excluding outliers. The Chauvenet method gives, for these arrival data, a low cutoff of -7.4 dB (and a high cutoff of 11.3 dB) which, from examination of Figure 31, excludes none of the data points. Using two standard deviations, the cutoffs of -4.2 dB and 8.1 dB exclude several of the outliers (10 of them, in fact), and the figure of merit becomes 1.18 dB.

Table 8. High and Low Cut-offs for the Two Methods for Excluding Outliers

Aircraft Type	Operation	Track Interval (feet)	Chauvenet		Two Standard Deviations	
			Low Cutoff, dB	High Cutoff, dB	Low Cutoff, dB	High Cutoff, dB
B727	Arr	0 - 20,000	-7.4	11.3	-4.2	8.1
		20,000 - 40,000	-11.1	10.7	-6.7	6.4
		> 40,000	-17.1	13.8	-11.5	8.2
	Dep	0 - 60,000	-19.8	18.9	-12.6	11.7
		> 60,000	-14.0	8.2	-9.7	3.9
B733	Arr	0 - 20,000	-2.4	7.7	-0.5	5.8
		20,000 - 40,000	-10.6	9.7	-6.5	5.6
		> 40,000	-16.7	9.9	-11.5	4.7
	Dep	0 - 30,000	-9.6	5.3	-6.7	2.4
		30,000 - 50,000	-14.2	8.1	-10.0	3.8
		> 50,000	-15.1	6.6	-10.4	1.9
B73S	Arr	0 - 20,000	-6.7	10.7	-3.6	7.6
		20,000 - 40,000	-9.5	12.0	-5.6	8.0
		> 40,000	-14.9	11.0	-10.3	6.3
	Dep	0 - 60,000	-16.4	12.1	-10.8	6.5
		> 60,000	-17.6	8.4	-12.5	3.3
B757	Arr	0 - 20,000	-10.2	12.7	-6.7	9.1
		20,000 - 40,000	-11.9	11.0	-8.0	7.2
		> 40,000	-16.9	10.0	-12.6	5.7
	Dep	0 - 50,000	-13.8	9.4	-9.8	5.4
		> 50,000	-14.3	5.0	-10.7	1.4
DC10	Arr	0 - 20,000	-5.6	8.8	-3.9	7.1
		20,000 - 40,000	-8.4	6.6	-6.3	4.5
		> 40,000	-21.2	2.6	-17.9	-0.8
	Dep	0 - 60,000	-4.0	8.5	-2.0	6.6
		> 60,000	-6.9	10.0	-4.2	7.3
MD80	Arr	0 - 20,000	-5.7	4.2	-4.6	3.0
		20,000 - 40,000	-11.4	3.8	-8.9	1.4
		> 40,000	-20.2	5.3	-17.5	2.5
	Dep	0 - 60,000	-8.8	9.8	-5.8	6.8
		> 60,000	-9.9	10.6	-7.3	8.0

For most of the data, the two different methods produce figures of merit that differ by less than 1 dB, though there are a few exceptions. The most noteworthy change is for B757 arrivals at 0 to 20,000 feet track distance where the figure of merit is 0.10 dB for the Chauvenet method and 1.78 dB when two standard deviations are used. Figure A14 shows that there are operations at less than 20,000 feet where the Difference in SEL (INM minus ANOMS) is as much as -5 dB to -15 dB. For these Denver data, differences of these magnitudes are rare, except at track distances over roughly 80,000 feet where measured levels are more likely to include non-aircraft noise (because the aircraft levels are lower) or where actual propagation effects may be considerably different from those assumed in the INM. It is therefore unexpected to find measured SEL so much higher than calculated SEL so close to the airport where measurements should be reliable.

When the airspace was examined for six of these B757 outliers, two may have been incorrectly measured (one was a go-round, and one had an unusually long duration), but the other four appeared reasonable. The B757 aircraft (models with Pratt & Whitney engines) are known to have a bleed air valve that opens under certain landing conditions to produce unusually loud sound levels.[5] All the flights checked were United Airlines, and hence presumed to have P&W engines.

Figures 41 through 44 depict the figures of merit graphically for easier comparison.[6] Use of two standard deviations for data exclusion appears to produce somewhat greater consistency across aircraft types than does use of Chauvenet's criteria. These figures show how agreement between INM computed SEL and measured SEL is generally better closer to the airport, and that the Difference becomes increasingly negative - the INM levels are increasingly lower than measured - at increasing distance from the airport. The goal of all following analyses is to determine the reasons for non-zero figures of merit, and to develop well-justified actions that can reduce the magnitudes of the figures of merit toward zero.

---

5 See "First Noise Monitoring Data Stirs Controversy about B757 Noise Levels" in *Airport Noise Report*, Vol. 5, No. 16, p. 117, August 27, 1993. "The first data report from the new noise monitoring system at Minneapolis-St. Paul International Airport showed that, at some monitoring stations, about half of the top 10 loudest noise level readings were caused by Stage 3 Boeing 757 aircraft on landing." The opening of the valve is reported to be automatic under certain operating conditions, and Northwest was working with P&W to develop a fix for the problem.

6 Note that for the departure figures of merit, the B733 points are not exactly comparable to those for the other aircraft. For this aircraft, the departure figures of merit were derived for three, rather than two intervals of track distance. The B733 departure values in these figures for < 60,000 feet are those computed for 30,000 to 50,000 feet.

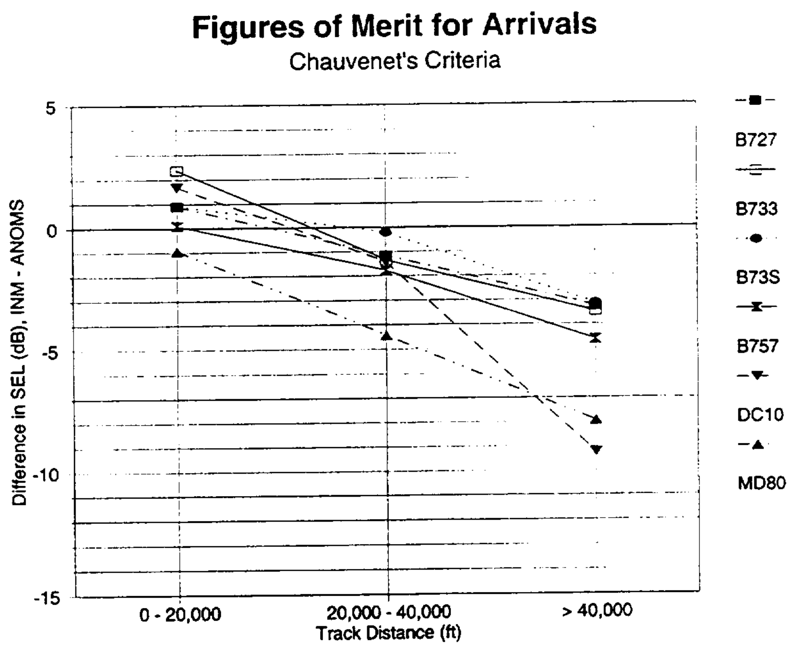

Figure 41. Figures of Merit Using Chauvenet, Arrivals

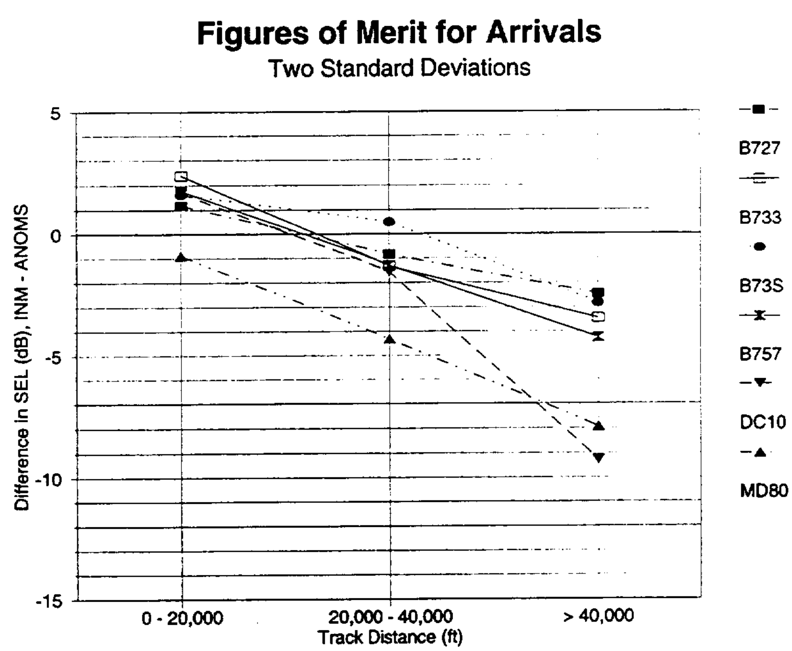

Figure 42. Figures of Merit Using Two Standard Deviations, Arrivals

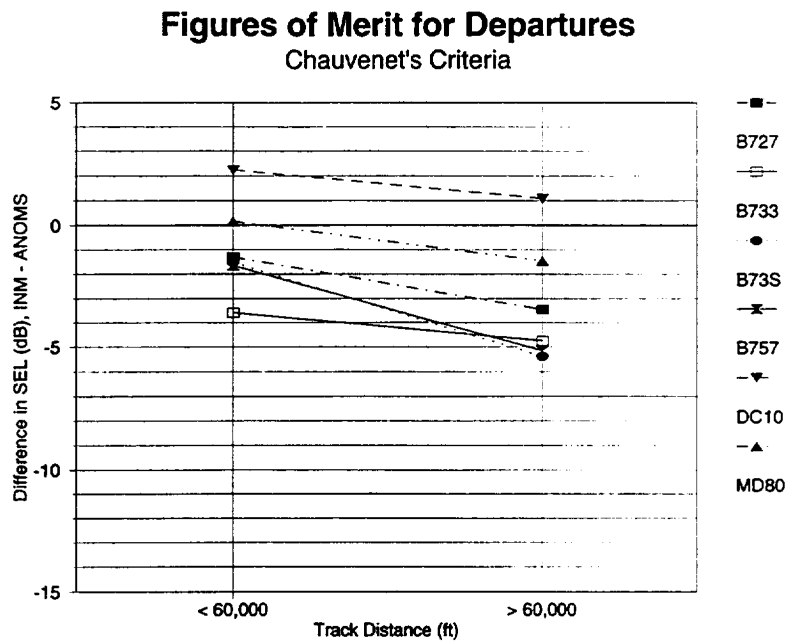

Figure 43. Figures of Merit Using Chauvenet, Departures

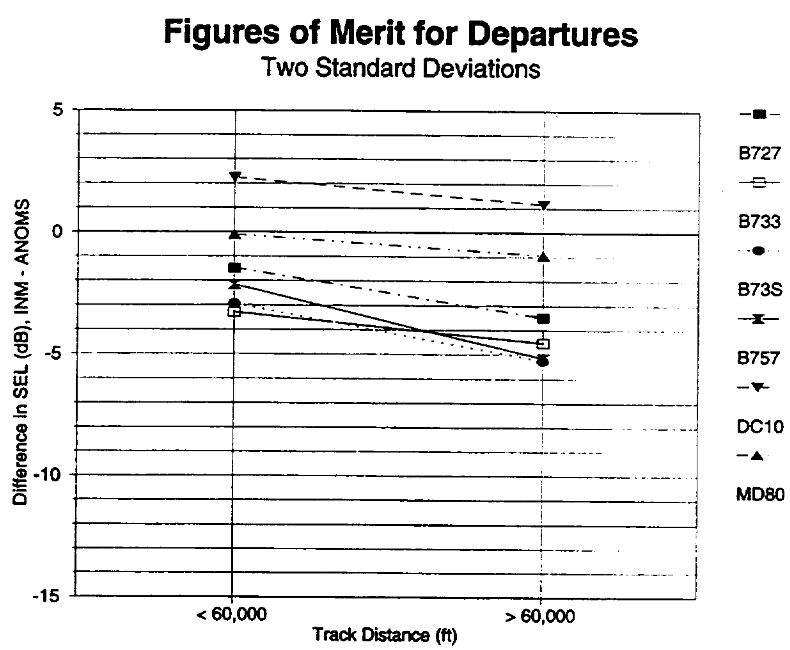

Figure 44. Figures of Merit Using Two Standard Deviations, Departures

5. APPLICATION OF METHOD TO MINNEAPOLIS DATA

5.1 Introduction

The preceding results from the analysis of Denver data may be affected by that airport's high altitude. Though the INM accepts, and makes some adjustments for non-sea level airports, these adjustments have never been fully verified. Hence, having developed and tested the analysis method, it was applied to an airport located more nearly at sea level. Minneapolis-St. Paul International Airport generously offered data, and these data, from May 1996 through April 1997 were used to develop an MSP analysis database of INM computed and ANOMS measured values of SEL.

Generally, the data were acquired and developed using the procedures described in Section 3. Three days were randomly selected from each of 12 months (though data were not usable for 3 out of these 36 days). Radar flight tracks were run through the INM (version 5.1), and "detailed grid" analyses produced to yield INM computed SEL values at each monitor, for each aircraft operation. The files of computed SEL and measured SEL were then combined to yield the analysis database of operations.

The Denver ANOMS software is a more recent version than that installed at MSP, and additional effort was devoted to the MSP data, checking the matching of measured events with flight tracks. Primarily, the synchronization of radar times and monitor times was checked and, for some days, adjusted through correlation of times of measured sound level maximums with times of radar determined point of closest approach. After these time adjustments, the measured events and flight tracks were re-matched to produce the final analysis database.

5.2 Data

Figure 45 shows the MSP runway configuration and RMT locations, and Table 9 lists the operations (takeoffs plus landings), by date, in the total database of measured and computed SEL. As with Denver operations data, these operations were then filtered and analyzed by aircraft type, by arrival and departure, by track length segment.

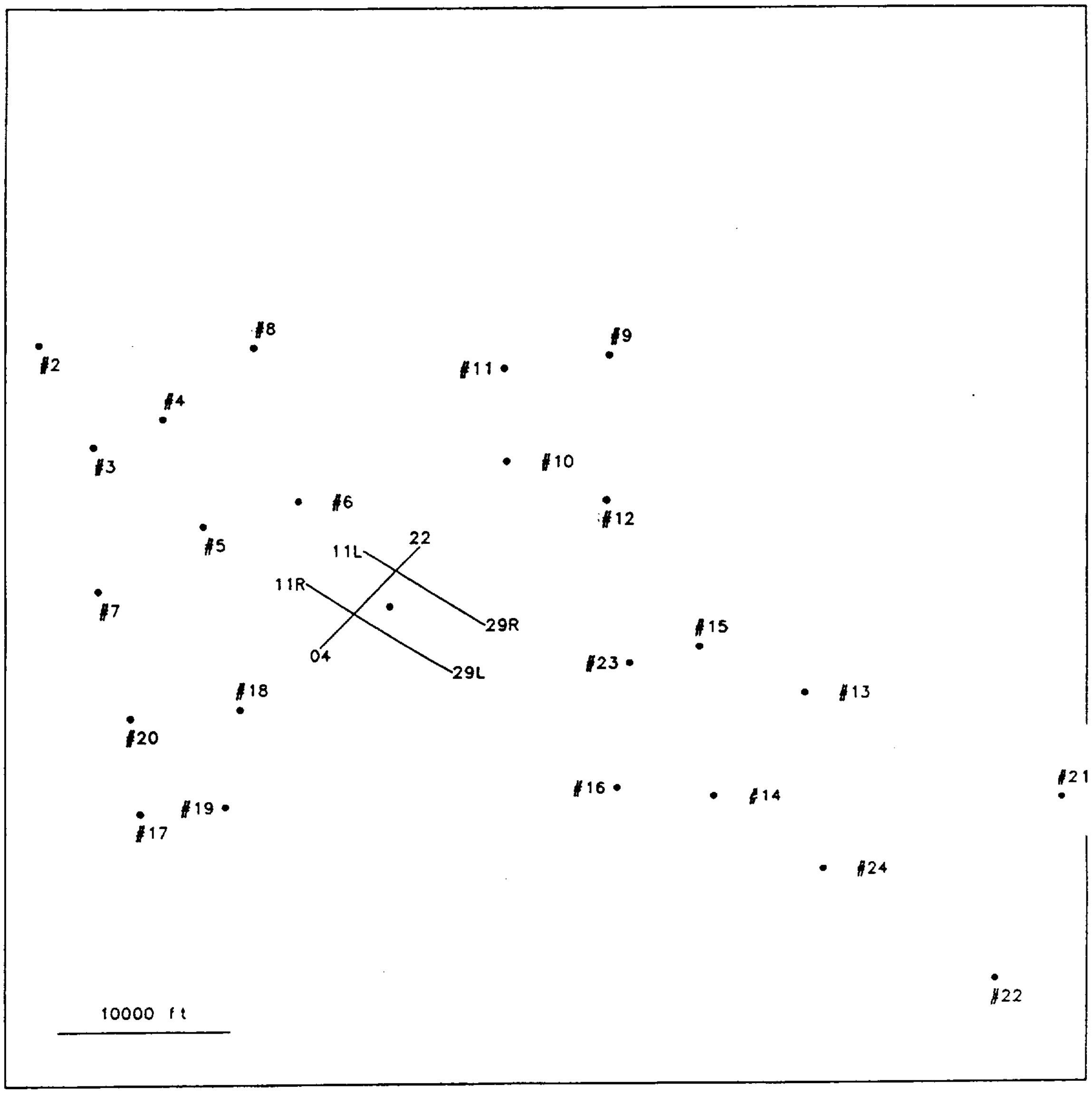

Figure 45. Remote Monitoring Terminal (RMT) Locations for Minneapolis-St. Paul International Airport

The total database, Table 9, contains all aircraft types captured on radar and simultaneously measured by the ANOMS RMTs. Table 10 lists the types having 100 or more operations in the database. This table also indicates the eight aircraft types that were chosen for the detailed analysis. Tables 11 and 12 give the final numbers of operations analyzed for each of the selected eight types. Table 11 gives totals before "filtering" for elevation angle and wind speed, while Table 12 gives the final filtered numbers used to compute the figures of merit. Note that the numbers of Table 11 are slightly different from those of Table 10; Table 11 excludes events that are either too long (>60 seconds) and likely include more than one operation, or unreasonably short (<8 seconds) to be valid.

Table 9. Total Numbers of MSP Operations Available, by Date

Date	Number of Operations
05/11/96	1158
05/12/96	1329
05/13/96	850
06/13/96	741
06/14/96	892
07/06/96	699
07/07/96	593
08/28/96	2665
08/29/96	2320
08/30/96	2209
09/14/96	1616
09/15/96	1753
09/16/96	2427
10/29/96	2514
10/30/96	1698
10/31/96	1711
11/11/96	1736
11/12/96	1651
11/13/96	1877
12/04/96	2710
12/06/96	2029
01/12/97	1083
01/13/97	1016
01/14/97	596
02/02/97	1219
02/03/97	2196
02/04/97	1972
03/20/97	857
03/21/97	2533
03/22/97	1606
04/03/97	2396
04/11/97	951
04/12/97	1324
Total	52927

Table 10. Aircraft Types in the Analysis Database with 100 or More Operations

Aircraft Type	Number of Operations	Selected for Analysis
DC9	22118	X
B727	9418	X
EA32	3000	X
B737	2922	X
B757	2638	X
DC10	2591	X
MD80	2251	X
SW3	840	
DH8	787	
FK10	764	
B73S	620	X
SF34	530	
BE02	488	
B747	331	
MD88	313	
DC8S	263	
SW4	259	
B73J	246	
BE80	216	
DC8	215	
HS25	145	
C650	135	
C402	115	
EA31	100	

Table 11. Selected Aircraft Types and Numbers of Operations in Full Sample - MSP

Aircraft Type (ARTS Designation)	Number of Departures	Number of Arrivals
M80	1340	1092
D10	1202	1297
72S / B727	4643	3978
B73S / 73S / B737	1391	1264
733 / 734 / 735	249	597
757 / B757	343	2175
DC9	11151	9328
EA32	847	2055
Totals	21166	21786

Table 12. Aircraft Types and Numbers of Operations Analyzed for Figures of Merit - MSP

(Includes only operations with point of closest approach 60 degrees or more above the horizon, relative to noise monitor)

Aircraft Type (ARTS Designation)	Number of Departures	Number of Arrivals
M80	490	262
D10	577	207
72S / B727	1138	926
B73S / 73S / B737	477	264
733 / 734 / 735	148	118
757 / B757	242	676
DC9	3894	1703
EA32	605	544
Totals	7571	4700

5.3 Analysis - Qualitative

It is useful to compare the DIA and MSP data sets from a qualitative perspective. This section provides several types of graphic presentations of the two data sets. By plotting INM computed *versus* ANOMS measured SEL values for each aircraft operation, it is possible to develop a sense for the general relationship between computed and measured values and between DIA and MSP data. Figure 46 is a scatter plot for departures in the Denver database. This figure presents, for each operation of the six DIA aircraft types analyzed (see Table 4), the ANOMS measured and INM computed SEL value. The diagonal line is the line of equality - points lying along this line have exactly equal measured and computed SEL values. The points are scattered about this line, but there appears to be a predominance of points below the line, meaning that for these points the measured SEL exceeds the computed SEL.

To further explore the relationship of measured to computed values, contours based on the density of these Figure 46 data points are plotted in Figure 47. This figure more clearly shows the tendency of the data to lie below the equality diagonal line. It should be recalled that because there are different numbers of data points for the different aircraft types (see Table 4), the location of the greatest density of points may be strongly influenced by these different sample sizes.

Figures 48 and 49 provide similar graphics for the MSP departure data. A notable difference between these data and that from DIA is caused by the different sound event detection modes. The DIA system uses a "floating" threshold as part of the algorithms used to capture aircraft produced flyover noise events in quiet background conditions. The MSP system uses a traditional fixed threshold as part of event identification; for all MSP monitors this threshold was set at 65 dB. Because aircraft produced SEL are about 10 dB greater in magnitude than the corresponding maximum level, MSP detects no events with SEL less than about 75 dB, as seen in Figure 48.

The analysis presented in this study, however, focuses on the SEL values produced by individual aircraft types, see Section 2.2. These preceding four figures contain all aircraft types and thus cannot be easily related to the figures of merit. Figures 50 and 51, on the other hand, present only the MD80 departure data that were used for analysis. (The contours in Figure 51 that lie at or above 110 dB, INM SEL, are a spurious creation of the graphing software.) These data are extracted from the total MSP database primarily by limiting the events to those that are produced by aircraft operations that are essentially "overhead" at the point of closest approach. ("Overhead" is determined by using operations with the elevation angle at point of closest approach of 60 degrees or greater, see Section 4.2.2.)

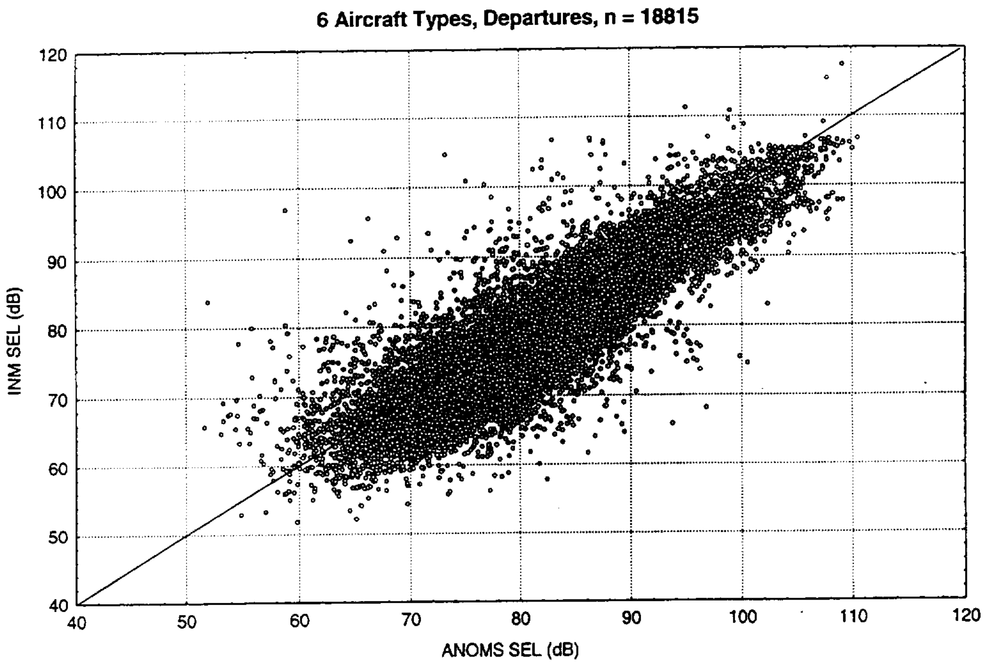

Figure 46. Computed *versus* Measured Departure SEL Values for Denver Analysis Aircraft

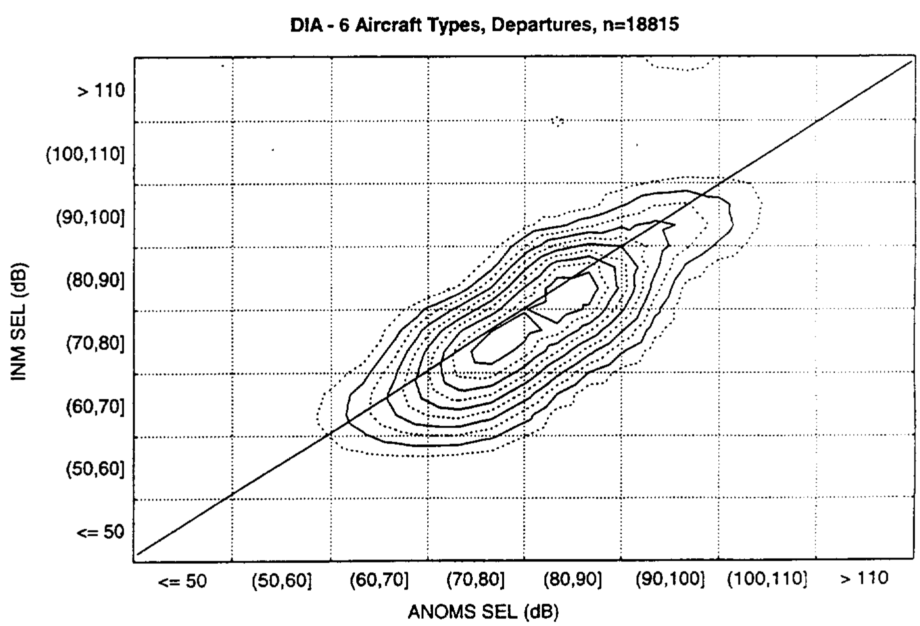

Figure 47. Departure SEL Data Density Contours for Denver Analysis Aircraft

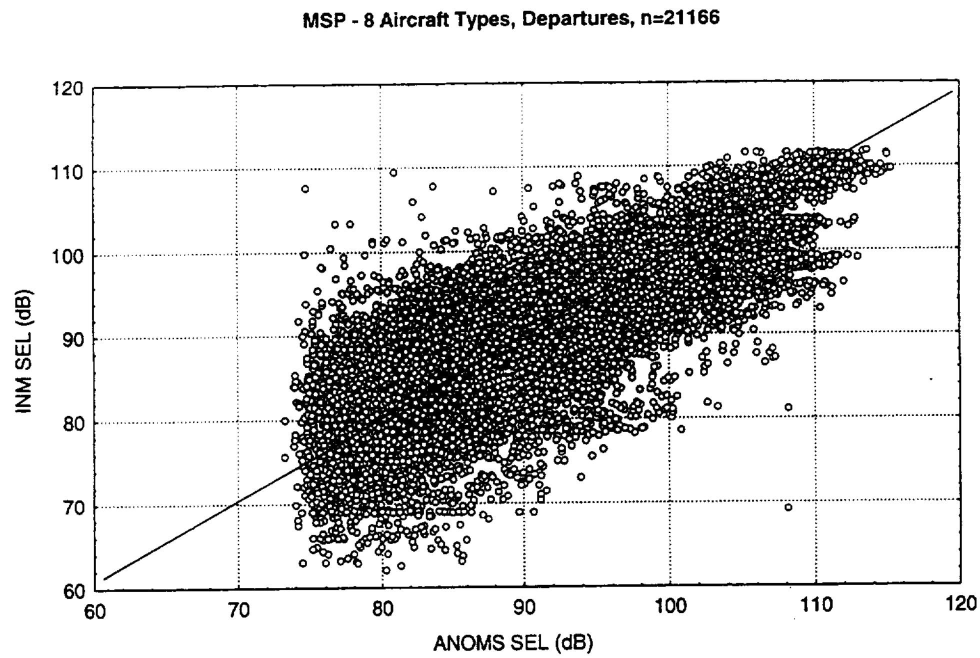

Figure 48. Computed *versus* Measured Departure SEL for MSP Analysis Aircraft

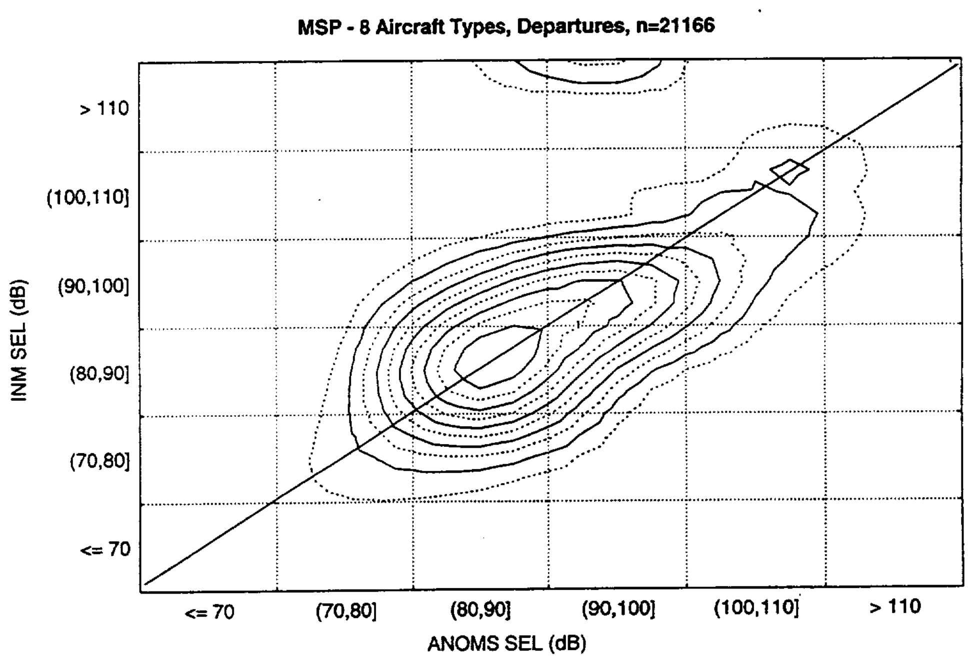

Figure 49. Departure SEL Data Density Contours for MSP Analysis Aircraft

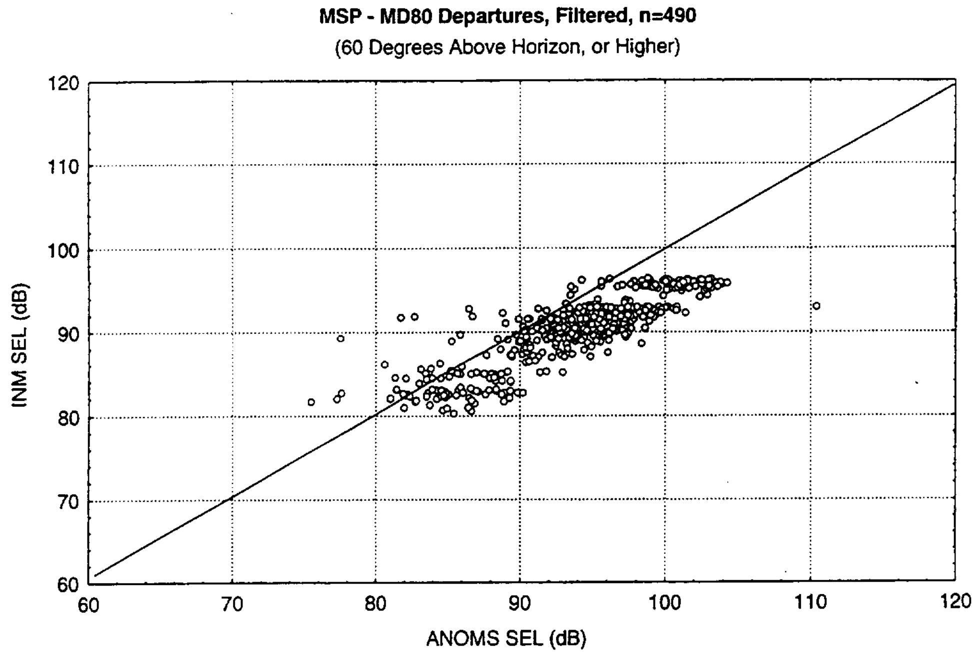

Figure 50. Computed *versus* Measured Departure SEL for MSP MD80 Aircraft

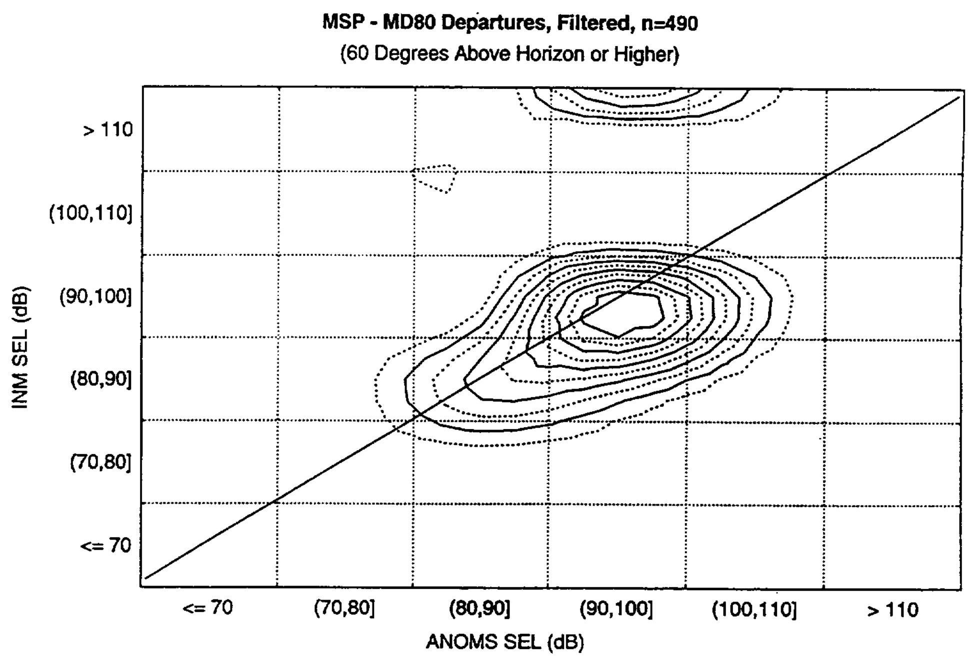

Figure 51. Departure SEL Data Density Contours for MSP MD80 Aircraft

These MD80 data can be qualitatively related to the figures of merit. Figure 50 shows how measured and computed SEL relate, as does Figure 51. A tendency for the measured levels to be roughly 5 dB greater than the computed levels is evident. The figures of merit, however, are computed for ranges of track distance, see Section 4.3. Figure 52 therefore presents the difference of computed minus measured SEL as a function of distance along the track. This figure also shows, with the solid vertical lines, the track distance ranges that were used to develop the figures of merit for MSP departures. (As with DIA data, these ranges are based primarily on the locations of the monitors relative to the track distances.) A figure of merit is computed (in the next section, see Table 13, page 63) for each of the four track distance ranges. The data of Figure 52 suggest that the difference is about -5dB at under 15000 feet; somewhat higher, roughly -4dB between 15000 and 28000; higher still, about -3dB between 28000 and 40000; and approximately -4dB beyond 40000.

Figure 53 provides similar data for MD80 arrivals. As evident, most of the data points fall in the first track distance interval, so that figures of merit computed for the two more distant intervals will be unreliable, see the next section.

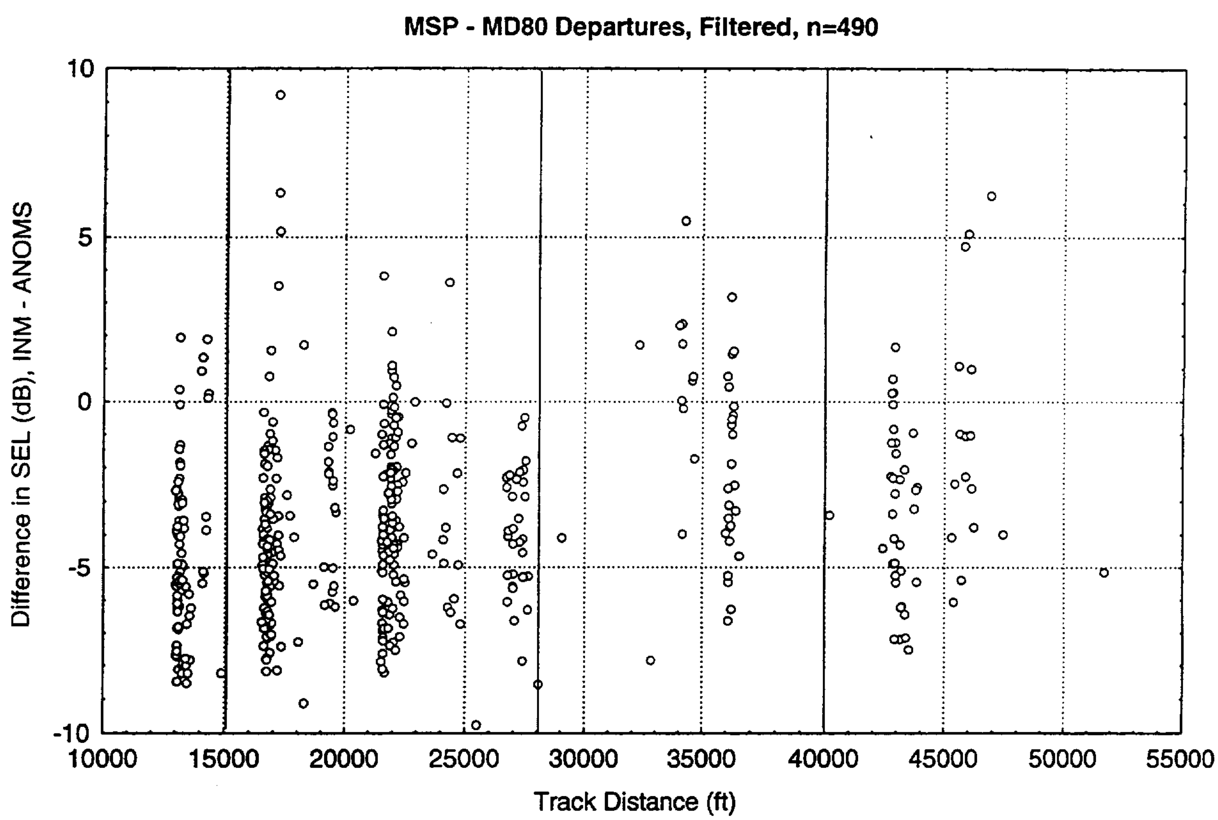

Figure 52. Difference in Departure SEL *versus* Track Distance for MSP MD80 Aircraft

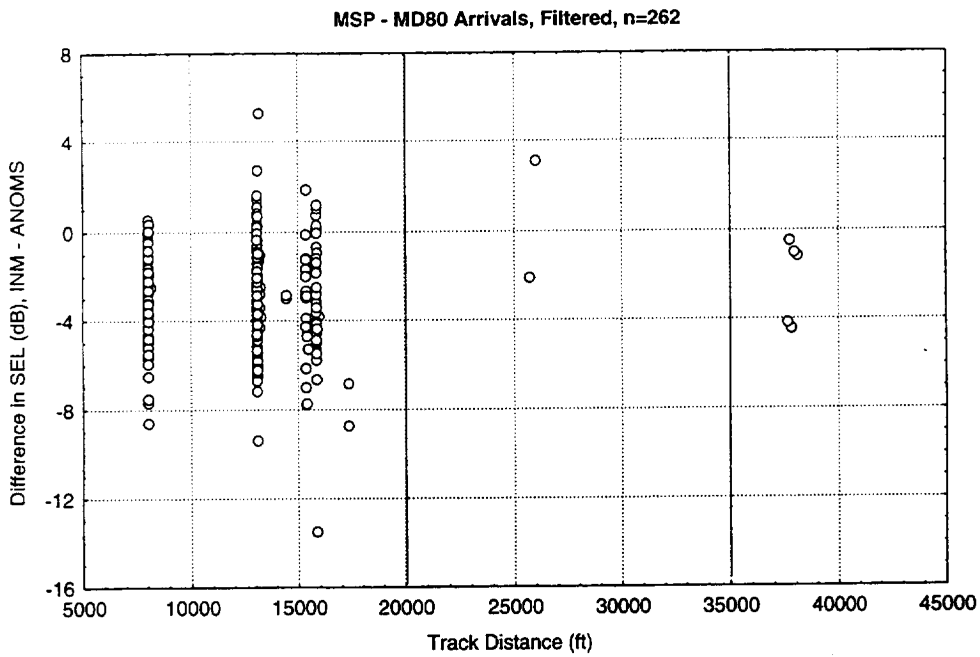

Figure 53. Difference in Arrival SEL *versus* Track Distance for MSP MD80 Aircraft

5.4 Figures of Merit for MSP

The figures of merit were computed for the eight selected MSP aircraft types, using the method described in Section 4. Data outside of two standard deviations were eliminated from analysis and Table 13 gives the details of the analysis results while Figures 54 and 55 graphically present and compare the DIA and MSP figures of merit for arrivals and departures. Table 13 gives for each MSP aircraft, by arrival or departure, by track interval, the total data points available (operations at 60 degrees or above), the data points within two standard deviations, the low and high values at two standard deviations, the figure of merit, and the 95% confidence range on that figure of merit. In Figures 54 and 55, only figures of merit are plotted that are derived from at least 20 data points. (Hence, for example, no figure of merit is plotted for the second two track intervals for MD80 arrivals in Figure 55, see also Figure 53.)

Comparing figures of merit from the two airports should be done with some care. First, note that the track distance ranges for which the figures of merit were computed are different. This difference is largely due to the different locations of the noise monitors. For example Denver's monitors tend to be at 20,000 to 80,000 feet from brake release, while MSP's lie almost entirely between 15,000 and 40,000 feet from brake release. Second, DIA is at approximately 5,400 feet above sea level, while MSP is at about 840 feet above sea level. The INM noise and performance data base is derived from sea level data, for sea level conditions, and the compensations programed into the INM for non-sea level conditions are untested. In general, the INM will compute louder departure levels on the ground for higher elevation airports (see Section 6.3, below), while arrival levels are unaffected.

The conclusion suggested by Figures 54 and 55 is that for these two airports, most of the aircraft types examined produce higher measured levels than those computed by the INM, using the standard departure and arrival profiles and departure stage lengths. These differences probably arise from a multitude of factors, and it is the challenge now faced to identify most probable causes of the differences. The next section presents some of the factors, and then briefly discusses the effects on INM computed levels of departure procedures, temperature and airport elevation.

Table 13. Figures of Merit by Track Interval, for Eight MSP Aircraft

Air Craft Type	Operation	Track Interval	Total Data Points	Data w/in 2 Standard Deviations	Lo-Cut	Hi-Cut	Figure of Merit	95% Confidence
B727	Arr	0 - 20,000	896	851	-5.7	6.1	-0.60	0.22
		20,000 - 35,000	8	8	-6.1	11.2	-0.19	5.75
		> 35,000	22	21	-4.3	6.4	0.75	1.15
	Dep	0 - 15,000	184	182	-6.7	7.0	-0.71	0.45
		15,000 - 28,000	674	638	-9.6	14.1	-0.60	0.68
		28,000 - 40,000	125	121	-5.8	15.0	2.42	1.45
		> 40,000	155	150	-7.1	10.0	0.34	0.84
B733	Arr	0 - 20,000	111	106	-3.5	3.4	-0.24	0.34
		20,000 - 35,000	2	2	-8.4	10.7	-0.35	8.96
		> 35,000	5	5	-5.9	5.6	-0.92	2.96
	Dep	0 - 15,000	26	26	-9.1	-0.7	-5.32	0.91
		15,000 - 28,000	97	89	-9.8	1.7	-5.16	0.63
		28,000 - 40,000	7	7	-11.2	0.7	-5.71	2.33
		> 40,000	18	18	-8.5	-0.8	-5.09	1.00
B737	Arr	0 - 20,000	255	243	-6.2	5.7	-1.01	0.45
		20,000 - 35,000	2	2	0.1	8.4	4.28	2.53
		> 35,000	7	6	-2.0	5.0	0.85	0.55
	Dep	0 - 15,000	105	96	-13.9	8.2	-1.19	0.91
		15,000 - 28,000	272	246	-18.9	11.1	-3.35	1.12
		28,000 - 40,000	27	26	-22.2	9.5	-5.70	4.21
		> 40,000	73	73	-21.8	5.6	-5.45	2.03
B757	Arr	0 - 20,000	662	643	-2.9	5.4	1.01	0.16
		20,000 - 35,000	2	2	-7.2	-0.3	-3.87	2.42
		> 35,000	12	12	-7.7	3.7	-2.72	1.84
	Dep	0 - 15,000	7	7	-9.1	1.8	-4.35	2.36
		15,000 - 28,000	195	181	-9.8	-0.1	-5.70	0.36
		28,000 - 40,000	38	35	-8.9	-1.4	-5.11	0.54
		> 40,000	2	2	-8.9	-8.7	-8.79	2.82
DC10	Arr	0 - 20,000	201	197	-4.4	3.5	-0.59	0.28
		20,000 - 35,000	3	3	-14.9	0.8	-8.44	6.02
		> 35,000	3	3	-6.5	2.1	-2.51	2.50

Air Craft Type	Operation	Track Interval	Total Data Points	Data w/in 2 Standard Deviations	Lo-Cut	Hi-Cut	Figure of Merit	95% Confidence
DC10	Dep	0 - 15,000	78	76	-6.4	2.0	-2.40	0.49
		15,000 - 28,000	378	353	-9.2	2.3	-3.89	0.34
		28,000 - 40,000	67	62	-10.1	4.0	-3.99	0.93
		> 40,000	54	50	-9.04	0.93	-4.42	0.61
DC9	Arr	0 - 20,000	1654	1571	-6.6	3.8	-1.91	0.14
		20,000 - 35,000	11	10	-10.2	3.9	-4.84	2.08
		> 35,000	38	37	-8.5	2.5	-3.49	0.95
	Dep	0 - 15,000	886	850	-13.9	7.2	-4.62	0.42
		15,000 - 28,000	2242	2019	-9.5	12.2	-1.06	0.45
		28,000 - 40,000	381	361	-10.6	8.6	-2.65	0.57
		> 40,000	385	368	-11.8	4.2	-4.41	0.44
EA32	Arr	0 - 20,000	529	506	-1.0	5.8	2.31	0.15
		20,000 - 35,000	4	4	-12.3	5.9	-4.56	5.30
		> 35,000	11	10	-8.9	5.1	-1.93	1.94
	Dep	0 - 15,000	83	79	-7.0	3.8	-2.38	0.60
		15,000 - 28,000	416	390	-8.3	1.5	-3.66	0.23
		28,000 - 40,000	78	74	-9.6	1.1	-4.64	0.62
		> 40,000	28	27	-10.7	-1.2	-6.13	0.91
MD80	Arr	0 - 20,000	255	247	-7.8	1.6	-3.54	0.32
		20,000 - 35,000	2	2	-6.8	7.8	-0.10	5.36
		> 35,000	5	5	-6.1	1.5	-2.56	1.78
	Dep	0 - 15,000	87	83	-9.6	0.5	-5.37	0.52
		15,000 - 28,000	311	290	-9.6	2.1	-4.56	0.32
		28,000 - 40,000	39	37	-8.2	4.7	-2.64	1.12
		> 40,000	53	50	-8.9	3.5	-3.78	0.78

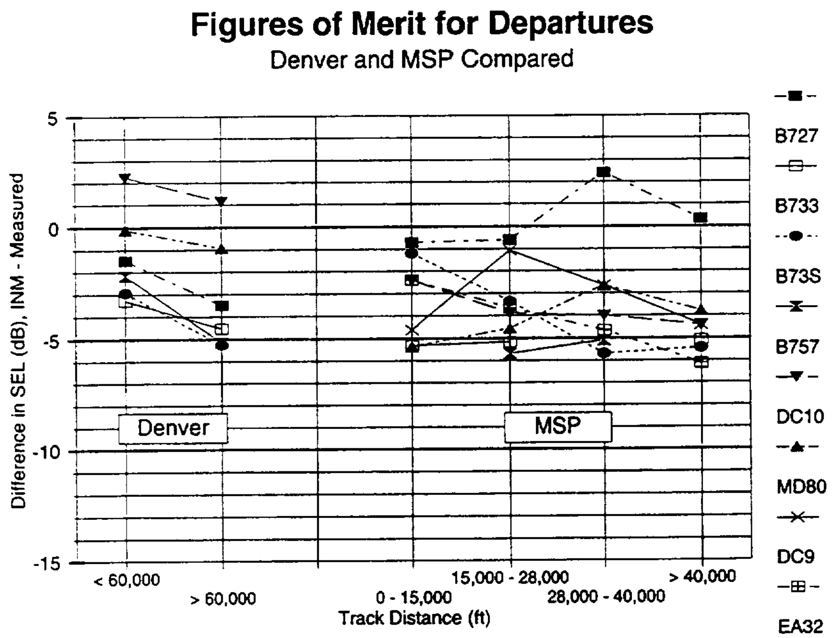

Figure 54. Figures of Merit for Departures - DIA and MSP Compared

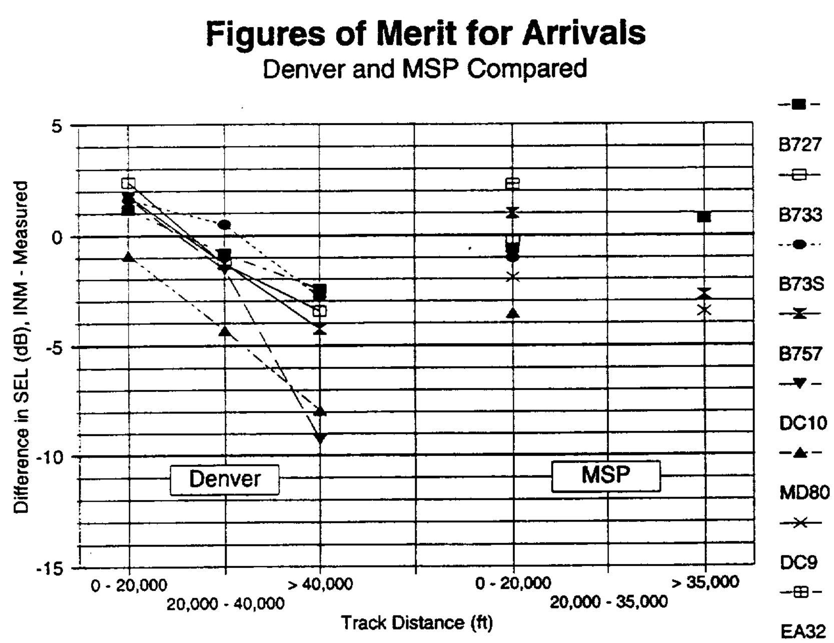

Figure 55. Figures of Merit for Arrivals - DIA and MSP Compared

6. POSSIBLE SOURCES OF DIFFERENCES

6.1 Introduction

Possible sources of the non-zero, negative figures of merit are many. The list below identifies those variables that may be most easily investigated using the existing DIA and MSP data, or those supplemental data that could aid in such investigations. The following sections then provide limited analyses of altering flight procedures, and of the effects of airport temperature and elevation.

Flight Procedures

These are the series of thrust and flap settings incorporated in the INM to define how an aircraft is flown during departure or arrival. All the analysis for the figures of merit used "standard" procedures. It is possible, and in some cases likely, that airlines fly the subject aircraft differently from these standards. The following section, Section 6.2, provides an initial examination of how different procedures affect the computed sound levels.

Temperature (air density)

Lift and thrust are a function of the air density. For all flights, airport temperature and pressure are known so that exploration of the effects of air density on measured levels is possible. Section 6.3 presents the effects of different temperatures on INM computed levels.

Airport Elevation

DIA and MSP are at very different elevations. The different measured sound levels at the two airports for a given aircraft type may help understand the significance and the effects of airport elevation. Section 6.3 also presents the effects of airport elevation on INM results.

Altitude profiles

Modeled aircraft altitudes differ from actual altitudes. Is this difference significant in terms of how the measured and computed sound levels differ? The data can be used to determine whether modeling incorrect altitudes is significant in determining the computed level.

Speed profiles

As with altitudes, speeds in the INM differ from actual speeds. The data can show the magnitudes of these differences and whether they have a significant effect on the computed levels.

INM Aircraft Type

The exact type of each measured aircraft cannot be known, and must be guessed using statistics for each operators fleet (see Section 3.3.3, OPS_FLT). Does incorrect assignment significantly affect computed levels, and hence affect the figures of merit?

Takeoff Weight

Historically, takeoff weight has been assumed by using the aircraft's "stage length" - the distance from the departure airport to the next arrival destination. There is little information suggesting that this surrogate for takeoff weight is realistic. Because takeoff weight is significant in determining thrust used (and sound level produced), it would be useful to examine whether modeled takeoff weights based on actual weights improve the modeling accuracy.

6.2 Flight Procedures

6.2.1 Introduction

Flight procedures assumed in INM modeling differ from the procedures flown at DIA. Figures 9 and 10 show that INM and actual departure altitudes may be similar on average, but variations of actual altitudes from INM altitudes may be significant, not only in terms of altitude but also possibly in terms of thrust and air speed. Hence, this initial analysis examines how variations from the "standard" INM flight procedures could affect calculated SEL. In other words, if modeled procedures more closely follow actual flight procedures, to what extent could the resulting changes in calculated SEL alter the figures of merit?

This examination of flight procedures was done with two different methods. First, new procedures were modeled using procedures reported by United Airlines pilots as flown during a three day period (28-30 November, 1995). Second, procedures were modeled to match altitude and speed profiles as recorded by ANOMS.

For each modeling approach, two changes in procedures are examined. In the first case (modeling pilot reported procedures), the modeling used thrust cutbacks occurring at the lowest typically reported altitude (1200 feet AGL) and at the highest typically reported altitude (2500 feet AGL). In the second case (modeling two actual 727 departures recorded by ANOMS), one flight had a relatively steep climb gradient after take-off (UAL flight 1479 on 18 November, 1995), the other flight had a relatively shallow angle departure (UAL flight 1614 on 18 November, 1995).

6.2.2 Modeling Pilot Reported Procedures

Background on Data Collection.

For a three day period (28-30 November, 1995) HMMH collected data on take-off procedures used by United Airlines (UAL) pilots departing from Denver International Airport. The data were collected by issuing questionnaires to the pilots on their procedures, then having the pilots furnish the requested information and return the questionnaires to UAL staff working with HMMH. A copy of a sample questionnaire is provided in Figure 56.

A possible problem with this method is its reliability. There is no way of knowing whether the pilots actually flew the departure procedures they reported they would fly. On the questionnaire, the pilots listed the altitude of the first throttle reduction from take-off power to climb power, but there is no way to determine how closely the pilots adhered to the reported procedures.

The reported departure procedures for the B727 were far more variable than those for the B737-300. Reported B727 procedures had throttle reductions occur from a low of about 1000 feet above ground level, to a high of 6,500 feet AGL; the B737-300 procedures consistently had throttle reductions occur at about 1,000 feet AGL. Personnel at UAL reported that this difference is due to the different degree of automation on the two aircraft.

UNITED AIRLINES

DENVER INTERNATIONAL AIRPORT
AIRCRAFT TAKEOFF THRUST SETTING SURVEY

APPLICABLE TO THE FOLLOWING AIRCRAFT:

B737-300
B737-200
B727

Attention: Flight Crews

United Airlines is a cooperative partner in developing solutions to the noise issues at Denver International Airport. In an effort to improve the accuracy of the computer model used to simulate and analyze DIA traffic flow, we need to capture exact takeoff and climb thrust settings. Please complete the following information for your flight and promptly forward this sheet to Bill Yantiss, DENFS, via Company Mail.

We are collecting information for a three-day period only. It is imperative that we receive information on ALL flights promptly. Do not adjust takeoff or climb thrust setting from established procedures. We need to capture information on a "typical" day. Thanks for your help!

GENERAL DATA:

UAL FLIGHT NO. 1614 AIRCRAFT TYPE 727 DATE 11/29/95

TAKEOFF GROSS WEIGHT (lbs) 165.6 TAKEOFF FLAPS 15

RUNWAY 17R TEMPERATURE (F°) 42 SURFACE WINDS 200/12

EPR/N1 DATA:

TAKEOFF EPR/N1: 2.07/2.09/2.07/94%

CLIMB EPR/N1: 1.95/92.2%

ALTITUDE (MSL) OF FIRST THRUST REDUCTION 8500'

MAIL TO: BILL YANTISS, DENFS

United Airlines Flight Center
7401 Martin Luther King Blvd., Denver, Colorado 80207

Figure 56. Form Used to Collect Pilot Reported Departure Procedures

The reported procedures did not include any information on the flap retraction schedule, the rate of climb, or climb profile requirements. Because this information was not part of the questionnaire, these parts of the modeling process had to be assumed. The INM basic calibrated airspeed-based flap retraction schedule was used to estimate the flap retraction schedule. Rates of climb and climb profiles were also based on the INM basic profiles.

Cutback Altitude Modeling.

Figure 57 shows all the pilot reported cutback altitudes for B727 aircraft for the three days. The low altitude cutback is modeled as 1,200 feet AGL and the high cutback as 2,500 based on these data. Several pilots reported thrust cutback altitudes significantly higher than the mean. These higher cutback altitudes occurred from 21,000 feet to 29,000 feet. These reported higher cutback altitudes were not considered because the pilots may have misunderstood the questionnaire and were reporting the thrust reduction which occurred in the transition from climb power to cruise power.

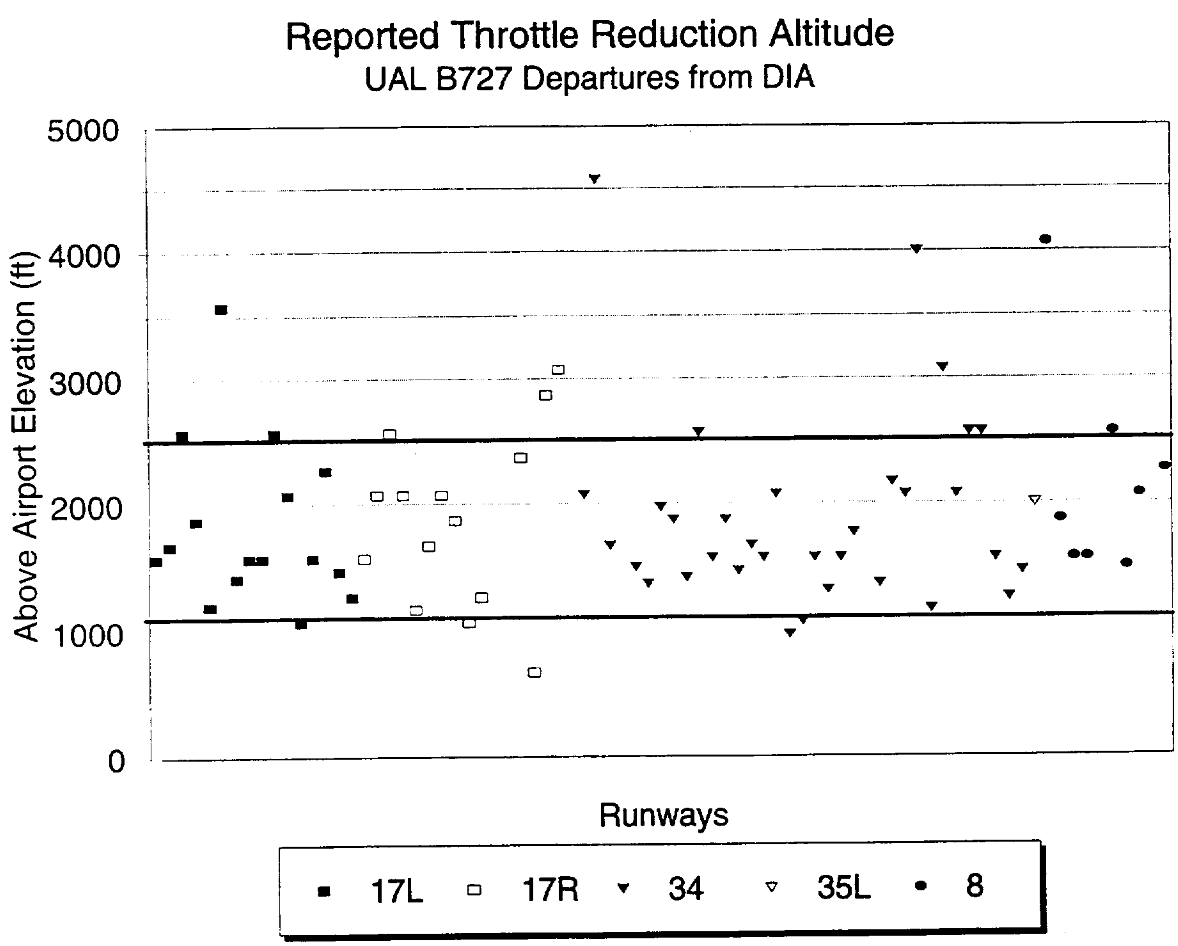

Figure 57. Reported Throttle Reduction Altitudes, B727

Modeling the Reported Procedures .

The standard INM profile for stage length one of the 727Q15 provided the starting point for modeling the reported procedures. The input variables were modified when the pilot's reported procedures differed from the standard INM profiles.

Most pilots reported an initial flap setting of 15 degrees. The INM standard flap setting for the B727 is 5 degrees. A transition from 15 degrees to 5 degrees was assumed to occur at the end of the first climb segment. The flap retraction schedule is typically based on airspeed and weight: above a particular airspeed, the associated flap (and slat) setting is no longer required to generate the additional lift needed at lower speeds, so the flap setting can be reduced. This relationship between airspeed and flap setting is given implicitly in the INM database.

The low altitude cutback departure was modeled with an initial climb segment to 1,200 ft, where the throttle change occurred, and was then modeled by following the INM standard procedure as closely as possible.[7] The high altitude cutback was modeled with a climb step to 1,000 feet, acceleration steps to 170, 200, and 210 knots calibrated airspeed (KCAS) - speeds where sequential flap retractions occur. Finally, the last portion of the high altitude cutback included a climb step to 2,500 feet, where the throttle change occurred, beyond which the standard INM procedure was used. In each case, 'throttle change' means a transition from take-off thrust to climb thrust. The throttle change occurred at the beginning of the appropriate segment.

Results of Modeling the Reported Procedures.

Comparisons of both the INM and the reported procedures are shown in Figures 58 through 62. Figure 58 shows the altitudes of the INM standard profile, Figure 59 shows the low (1,200') cutback profile and Figure 60 shows the high (2,500') cutback profile. Figure 61 shows the SEL directly under the flight track as calculated by the INM for all three cases. The SELs for the two pilot reported cases differ from the standard INM case depending upon where the thrust change from take-off power to climb power occurs. The thrust change for the low cutback case occurred at about 17,000 feet from brake release. The INM standard profile has its throttle change at about 27,000 feet from brake release. The thrust change for the high cutback case occurred at about 37,000 feet from brake release. The effects of these different cutback locations are clearly evident. Figure 62 shows the difference in SELs for the two reported procedures relative to the INM standard profile. Figures 61 and 62 show that variations in the throttle change criteria could have significant local effects, up to ±4 dB, on the SEL. This magnitude is comparable to the magnitudes of some of the figures of merit, thus suggesting that differences between INM and actual procedures could be responsible at some locations for some of the differences shown by the figures of merit. It should be noted, however, that these effects of different climb out procedures apply to track distances of under 40,000 feet. Figure 54 shows that for both Denver and MSP, there are significant differences between computed and measured SEL at track distances greater than 40,000 feet.

---

7 The INM standard procedure up to 3,000 feet is a climb step to 1,000 feet, acceleration steps to 170 and 200 KCAS, where the throttle change occurs, then an acceleration to 210 KCAS, and a final climb step to 3,000 feet.

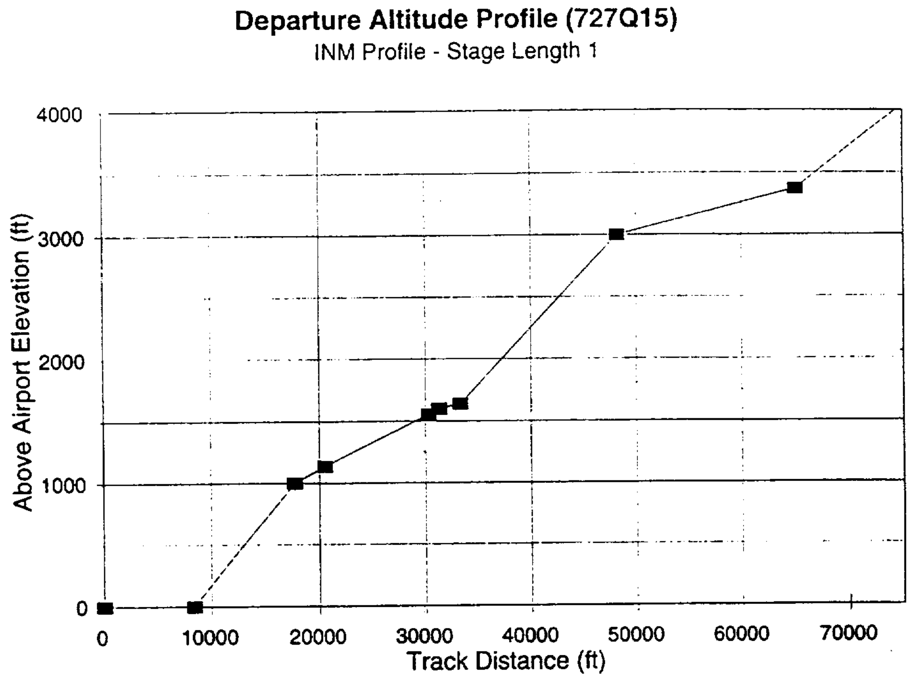

Figure 58. Standard INM Departure Altitude Profile, B727Q15

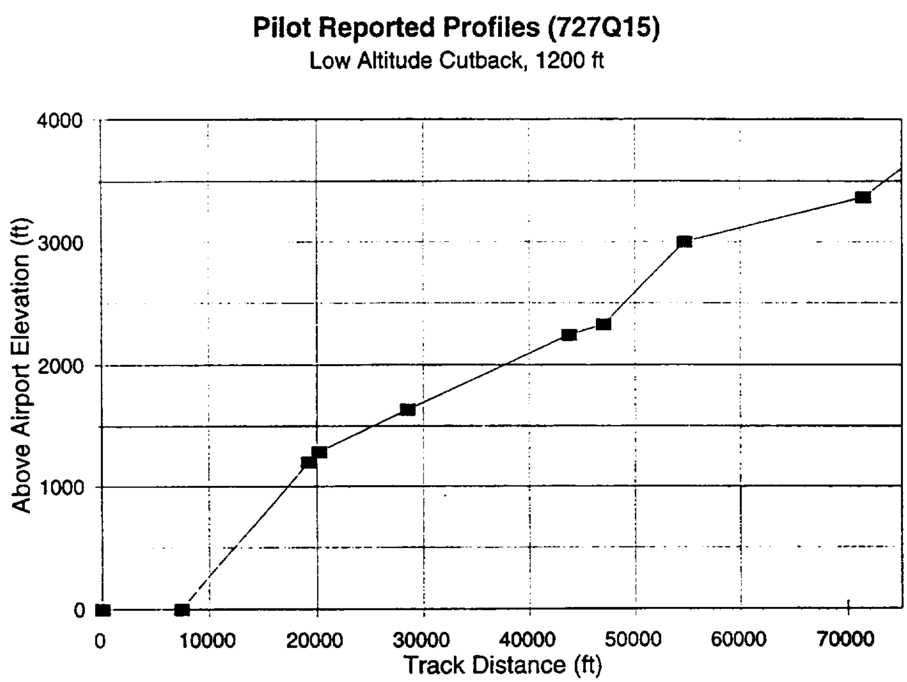

Figure 59. Resulting Altitude Profile, Low Altitude Cutback

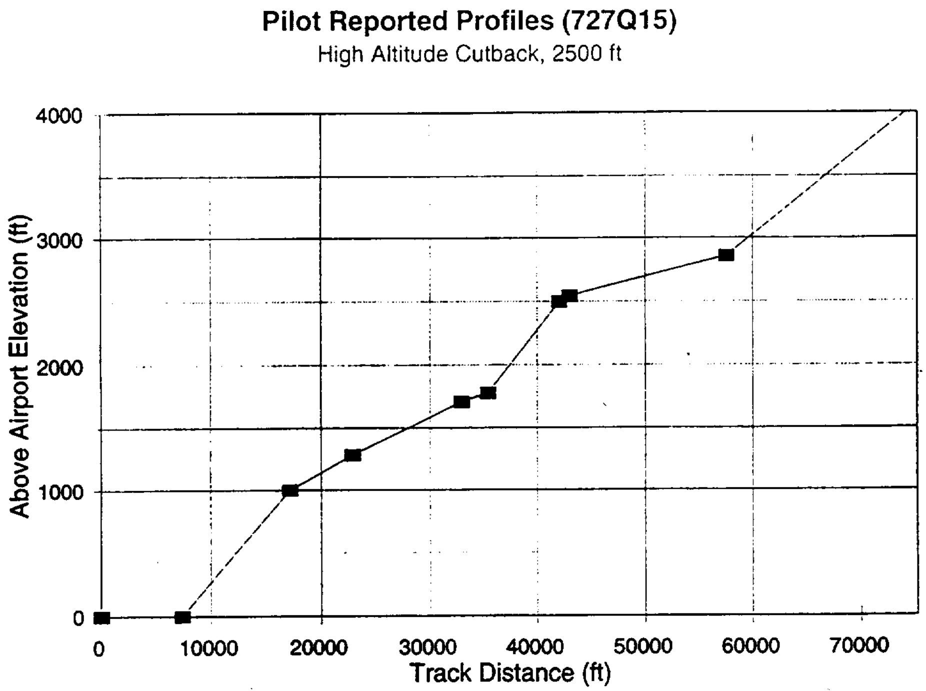

Figure 60. Resulting Altitude Profile, High Altitude Cutback

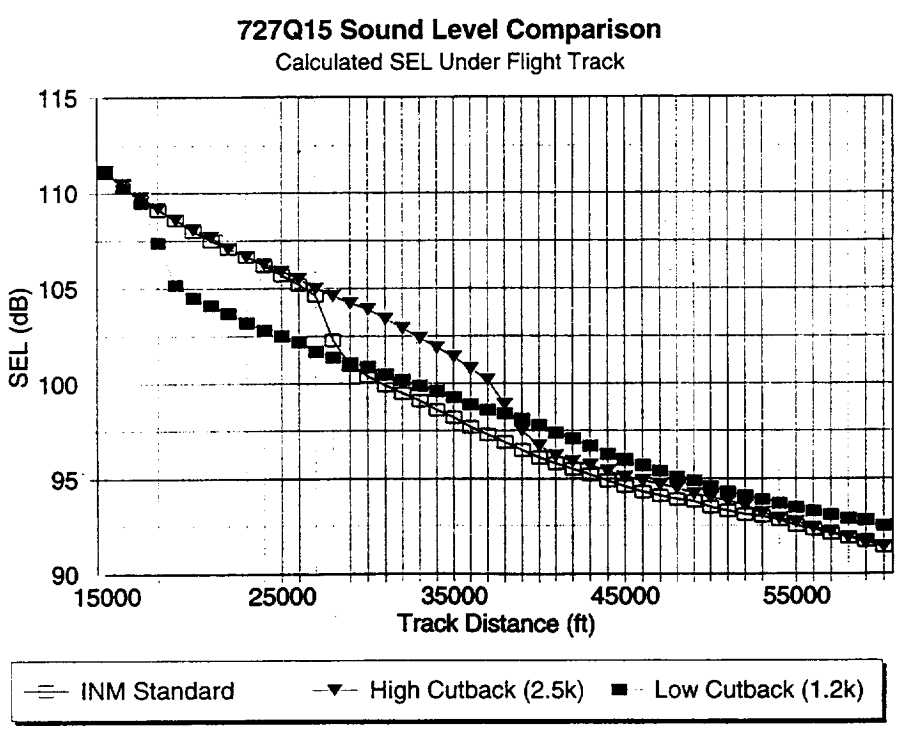

Figure 61. INM Calculated SEL under Flight Track, Pilot Reported Procedures

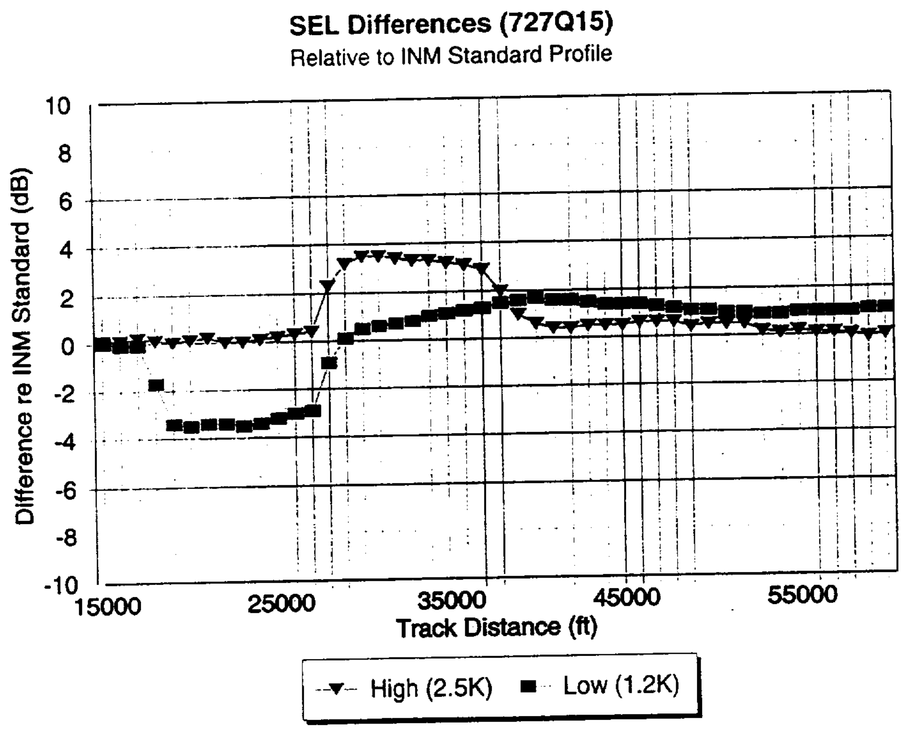

Figure 62. Difference in SEL Between INM Standard and Pilot Reported Procedures

6.2.3 Modeling ANOMS Recorded Procedures

Background on ANOMS data collection.

Departure flight data collected by the ANOMS system provided empirical altitude and speed profiles for analysis. Two departures were selected for modeling and comparison with the INM standard departure procedures: UAL 1479 on November 18, 1995 and UAL flight 1614 on the same day. Flight 1479 was chosen as a flight with a relatively high overall rate of climb, flight 1614 had a lower overall rate of climb.

Figures 63 and 64 show the ground speed and altitude information for these two flights as provided by the ANOMS system. New flight procedures were developed to match these profiles as closely as possible while keeping other variables (particularly thrust and flap settings) within reasonable limits. Note that matching these profiles required use of thrust values which, in some cases, were greater that the INM standard profile thrusts, even when the INM standard thrust values are given as 'maximum take-off' thrusts.

Examination of these two flights showed that, as with INM standard profiles, the profiles could be reasonably divided into climb segments and acceleration segments. Figures 65 and 66 show how the profiles were divided into climb or acceleration segments. The ANOMS reported ground speed was assumed equal to the INM true airspeed.

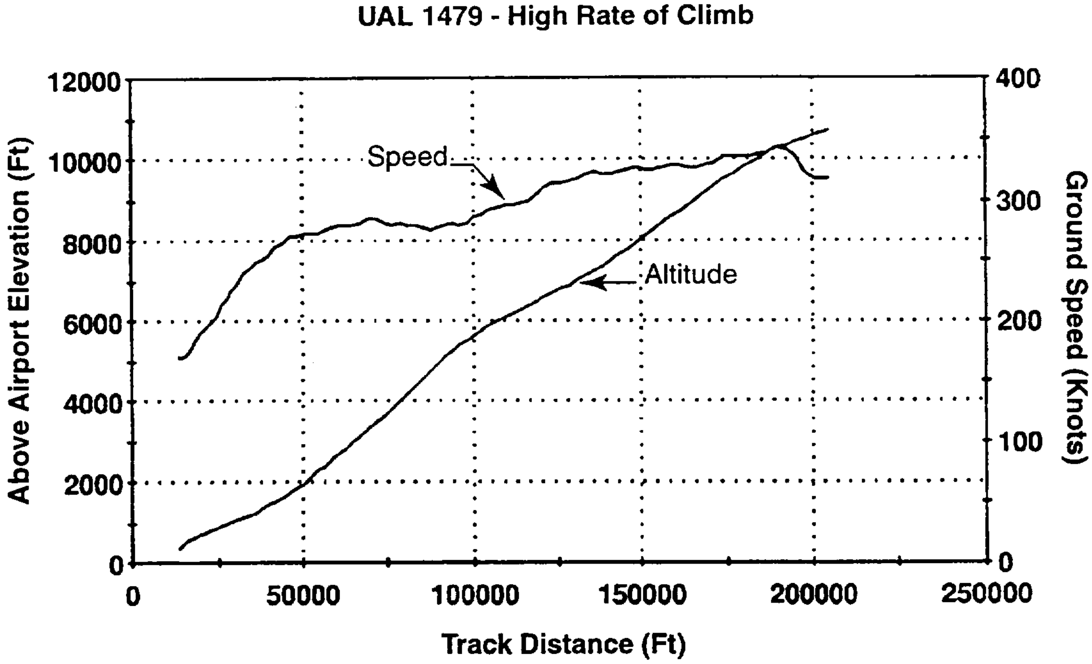

Figure 63. ANOMS Speed and Altitude Profiles, UAL 1479

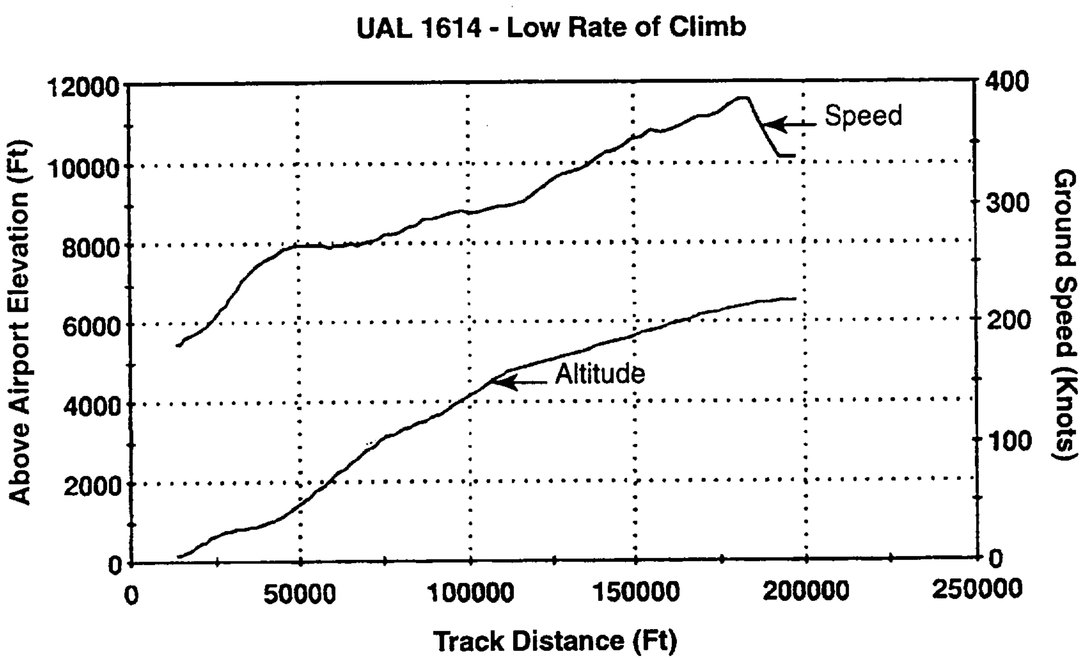

Figure 64. ANOMS Speed and Altitude Profiles, UAL 1614

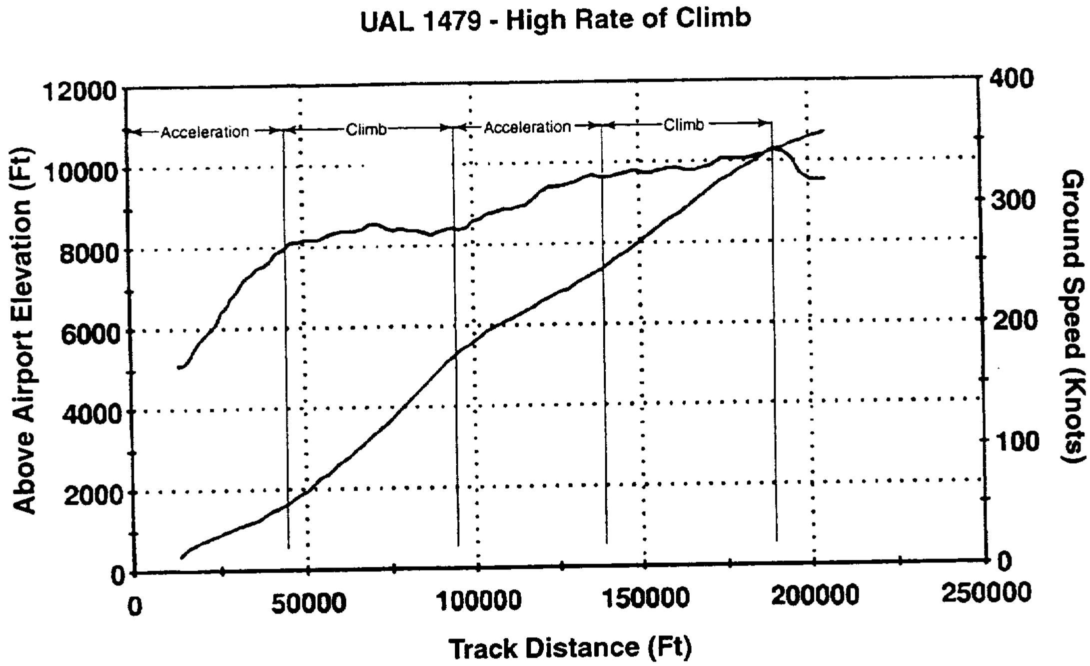

Figure 65. Modeled Division into Climb and Acceleration Segments, UAL 1479

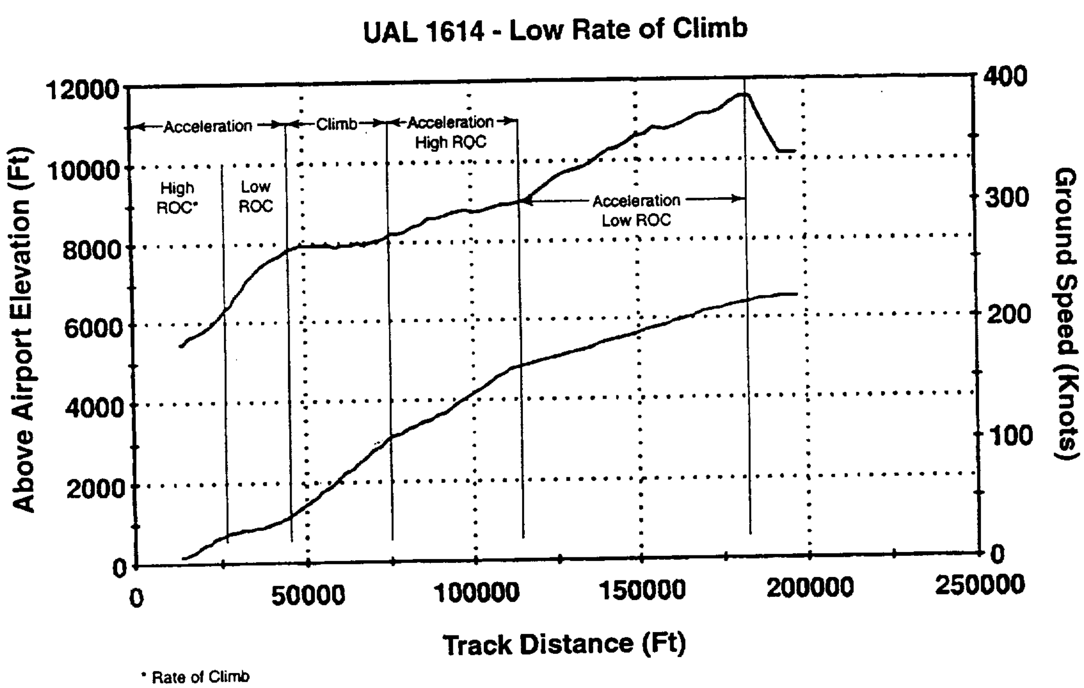

Figure 66. Modeled Division into Climb and Acceleration Segments, UAL 1614

Profile Development.

To make the INM ground roll mimic the implicit ANOMS ground roll[8], the "B" parameter (of SAE 1845 equation A6) was modified. It was changed from its nominal value of 0.008078 to 0.012. This was the only aircraft parameter changed. The same change was made to both modeled flights. This change increased the modeled takeoff roll by 50%.

The initial flap setting for both flights was 15 degrees, not the 5 degrees setting which is used in the INM standard profile. This value was based on the information collected from the UAL pilots which showed a preference for using 15 degrees of flaps at Denver (see Section 6.2.2).

The modeled flap retraction schedule was based on the same logic used in the pilot reported procedures section. Flaps were not reduced until speeds were high enough to do so. Once reduced to a certain setting, flaps were not extended again. Because the ending speeds for each segment for the two flights were different, the flap retraction schedules were also different.

The performance parameter with the greatest variability was the thrust setting. "MaxTakeOff" thrust was only used on the ground roll. All other profile segments used "UserValue" thrusts. These "UserValue" thrusts were determined by a trial-and-error method to provide a match between the INM reported altitude and airspeed and the ANOMS reported altitude and ground speed at the same track distance. The resulting thrusts are shown in Figure 67 The modeled thrusts differ significantly from the INM thrusts, particularly for the slower climbing aircraft (UAL 1614).

Results of modeling the recorded procedures.

Figure 68 shows the SEL values under the flight track for the three modeled departures, and Figure 69 presents the SEL differences between the modeled flights and the INM standard departure profile. UAL1479 climbed while also decreasing thrust from 14,000 lb/engine to 11,000 lb/engine over 60,000 feet. UAL1614 climbed more slowly while decreasing thrust from 14,000 lb/engine to 9,000 lb/engine for the first 30,000 feet. The relatively flat part of the UAL1614 SEL plot (from about 25,000' to about 40,000') occurred while the aircraft was *increasing* thrust by 1,000 lb/engine while gaining 400' of elevation and 50 knots of airspeed. Interestingly, the higher thrust of UAL 1479 made that departure always louder than the slower climbing UAL 1614.

6.2.4 Conclusions

These analyses show that different departure procedures, as modeled using the INM, can produce significantly different SEL values on the ground. Future efforts should be devoted to developing "best fit" procedures for the various aircraft types, for arrivals and departures, and exploring how such profiles, when used in the INM, affect the figures of merit.

---

8 The ANOMS radar does not track aircraft on the ground. The ANOMS (actual) ground roll was estimated by extrapolating back the first climb segment to the ground. This is the same method shown in Figure A1 of SAE-1845.

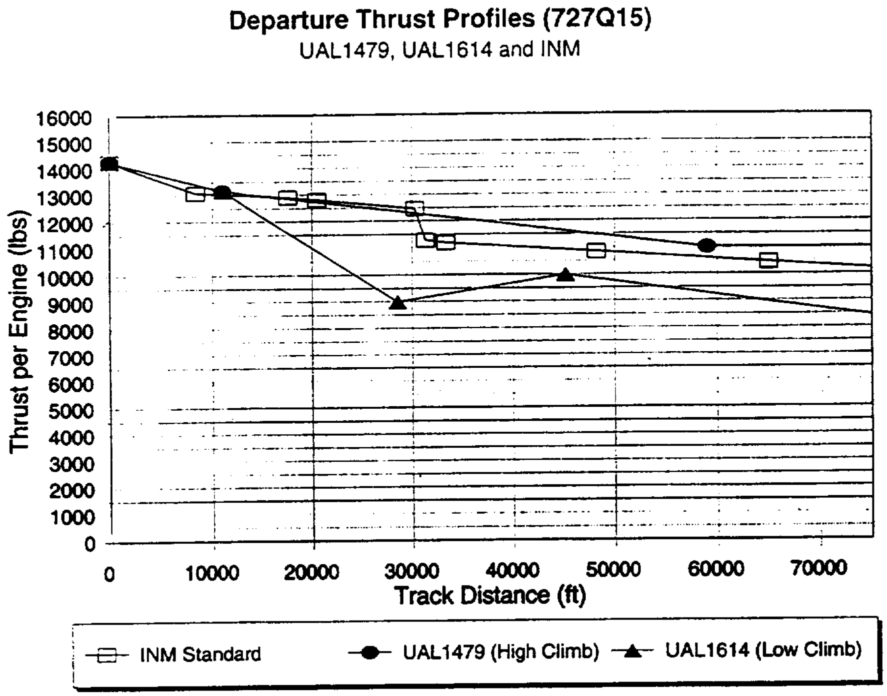

Figure 67. Resulting Thrust Profiles Compared with INM Standard

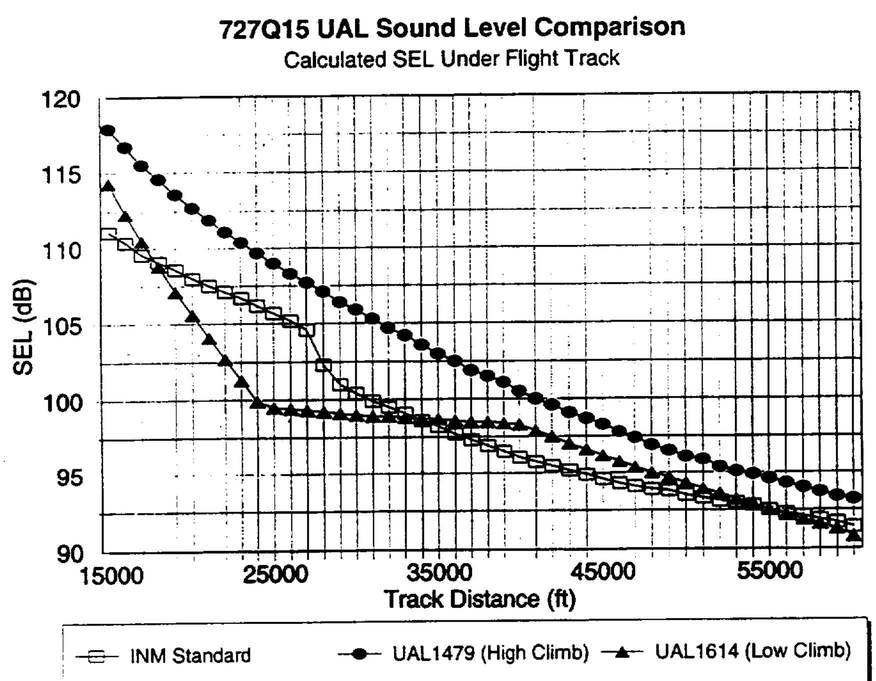

Figure 68. INM Calculated SEL Under Flight Track - Two UAL Departures

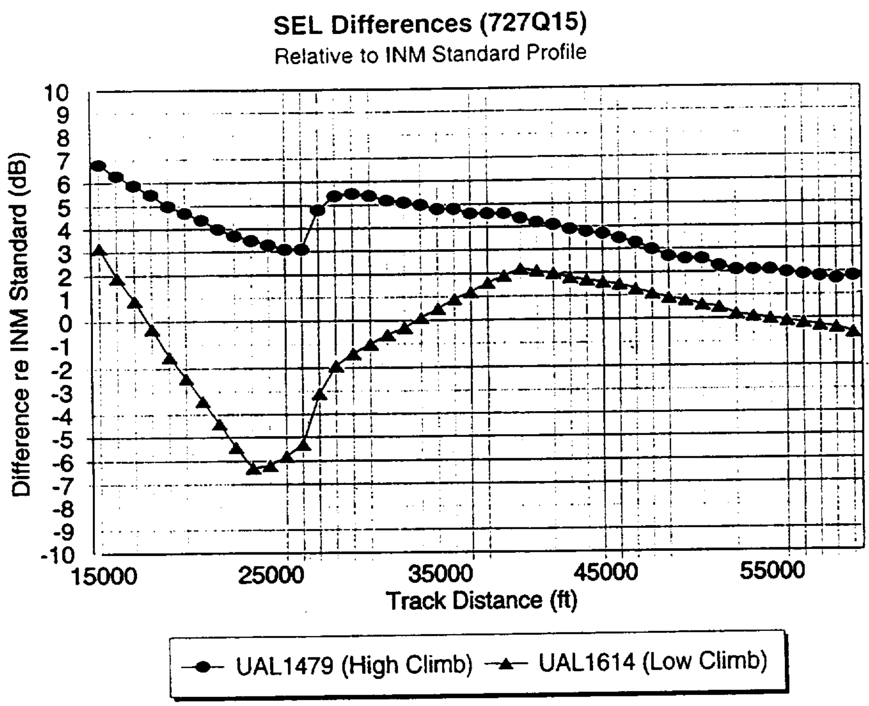

Figure 69. Differences in SEL between INM Standard and Two UAL Departures

6.3 Effect of Temperature and Altitude on Standard profiles

Airport elevation and temperature affect INM calculated SEL values. To better understand these effects, a single departure of each of nine aircraft types was modeled for different temperatures and airport elevations. For the same starting elevation (DIA, 5431 MSL), the temperature at ground level was modified and the change in the resulting SEL computed at a specific location. For this analysis, a right cross-wind departure track from Runway 34, which passed over RMT 13 at a track distance of 72,700 feet was modeled. The results of varying the temperature (while keeping airport elevation constant) are shown in Figure 70. Four temperatures are used : 0°F, 39°F (the standard day temperature at Denver elevation), 59°F (the temperature used for the INM runs in this study), and 90°F. Although the results vary with aircraft type, results do not indicate a strong temperature dependence in the INM on SEL. It is unlikely that INM modeled temperature effects are significant enough to affect the figures of merit.

INM calculated SEL is a function of the thrust and of the altitude of the aircraft. For the nine aircraft types modeled and shown in Figure 70, the changes in corrected net thrust and their altitude (AGL) at which they pass over RMT 13 are shown in Figures 71 and 72, respectively. These two figures show that both the thrust and the altitude decrease with increasing temperature (and therefore with increasing density altitude); these combined effects result in the SEL values shown in Figure 70.

The effects of airport elevation were examined in a similar manner. Figure 73 shows the change in SEL from that calculated for a sea level airport for the nine aircraft types for three different field elevations: 0 feet MSL, 2500 feet MSL and 5431 feet MSL. The temperature for each of these cases was 59°F. The same flight track and location point were used as in the temperature study. The SEL increases in all cases as the field elevation increases; the effect varies depending on the aircraft type. For some aircraft types, the highest elevation (Denver's) produces changes significant enough to affect the figures of merit. All aircraft are calculated to be louder in Denver than at sea level. Note that the increase in SEL that would result for MSP at 841 feet is less than ½ dB.

The effect of airport elevation on thrust is shown in Figure 74. Some aircraft show an increase in thrust with altitude, others show a decrease. The aircraft with the most increase, the MD81, uses engines of the same family as the aircraft with the most decrease, the 737D17[9]. The difference is that the MD-81 is modeled with no G_2 term, the 737D17 contains a negative G_2 term. Figure 75 shows the effect of airport elevation on altitude at the RMT. In all cases, the altitude of the aircraft at the RMT is reduced.

9 Both use Pratt & Whitney JT8D engines. The 737D17 uses JT8D-D17 engines, the MD-81 uses JT8D-209 engines.

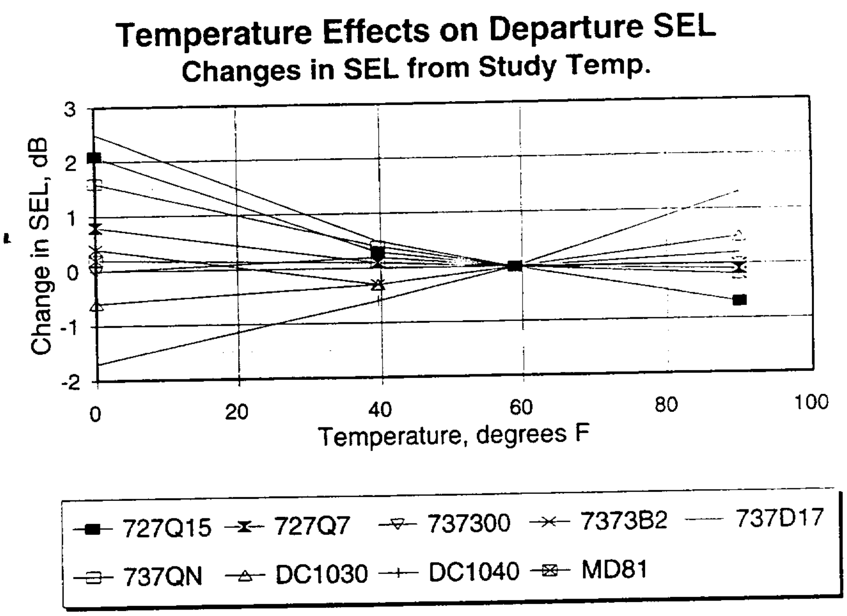

Figure 70. Changes in INM SEL Produced by Changes in Temperature as Compared with Modeled Temperature of 59°F

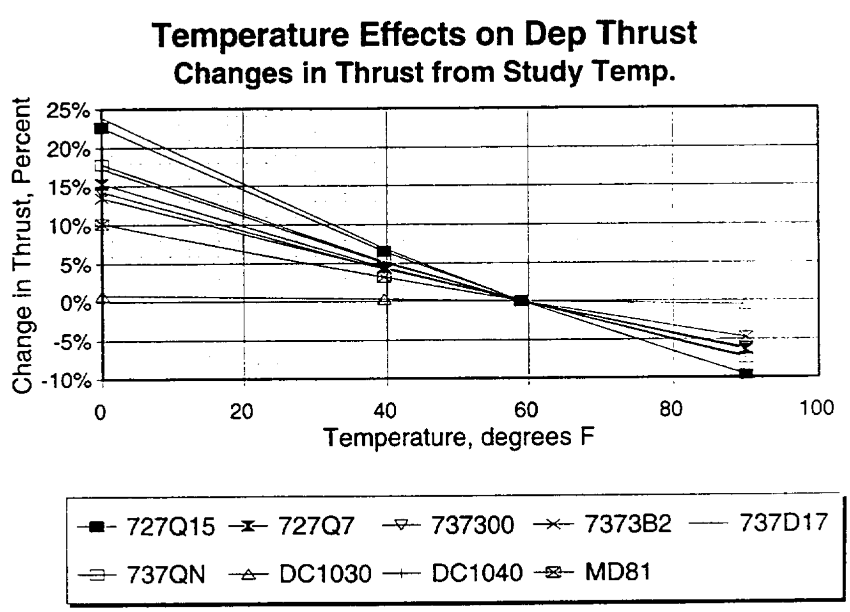

Figure 71. Changes in Corrected Net Thrust Due to Changes in Airport Temperature

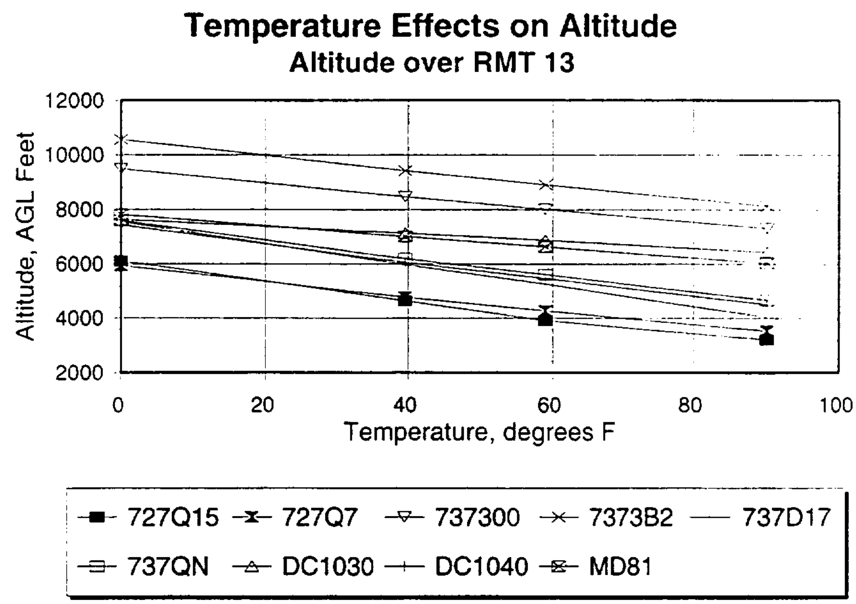

Figure 72. Changes in Aircraft Altitde at RMT 13 Due to Changes in Airport Temperature

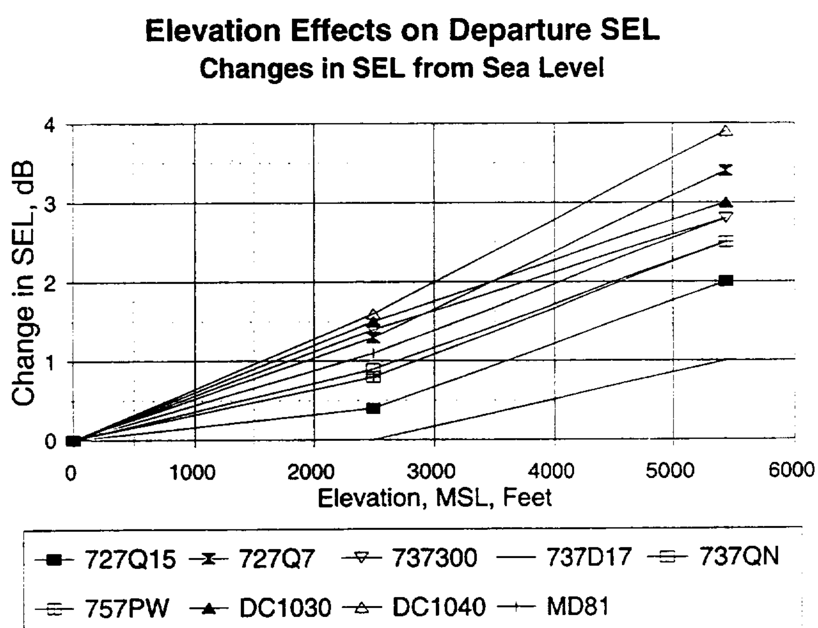

Figure 73. Changes in INM SEL produced by Changes in Airport Elevation as Compared with at Sea Level Aiport

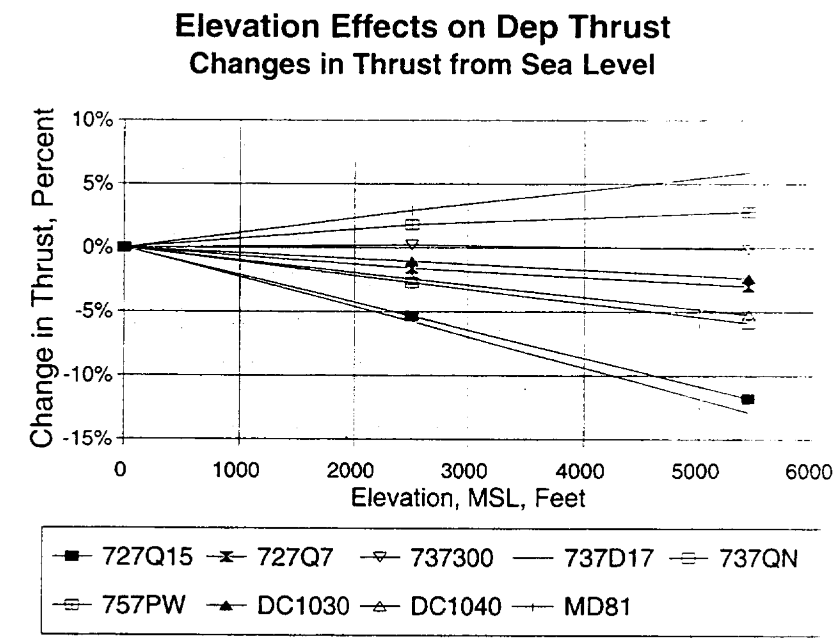

Figure 74. Changes in Corrected Net Thrust Due to Changes in Airport Elevation

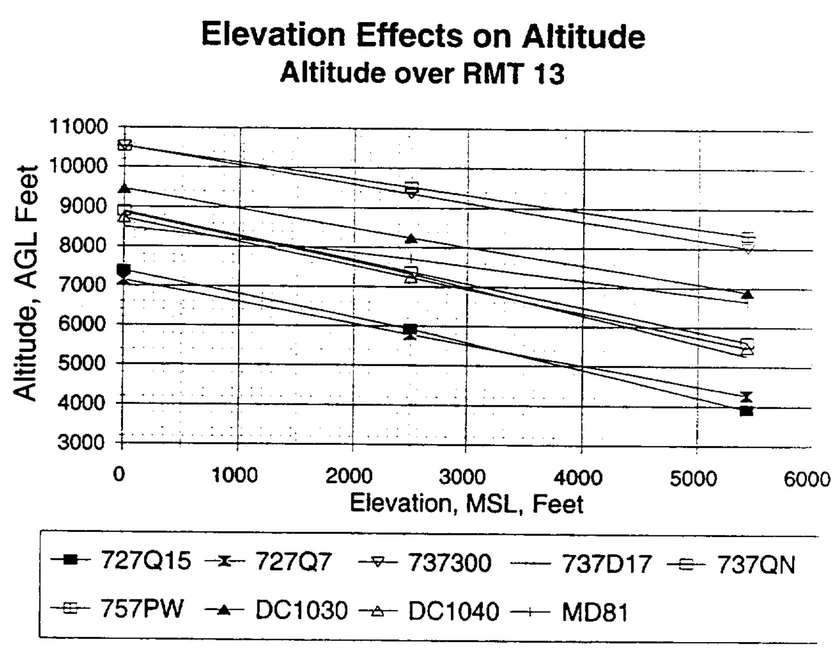

Figure 75. Changes in Aircraft Altitude at RMT 13 Due to Changes in Airport Elevation

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The preceding analyses focused on development of the "figures of merit" - sound energy based differences between measured and INM computed aircraft produced sound levels. The figures of merit summarize by their sign and magnitude, the difference between the measured and computed SEL, by aircraft type, by distance from the airport (track distance), for arrival or departure,. Figures of merit greater than zero indicate that computed levels are greater than measured levels, suggesting that the INM, as used, overpredicts sound levels relative to measurements. Negative figures of merit indicate underprediction.

The summary results are presented in Figures 54 and 55, page 64. For most aircraft types analyzed, for most track distances, the figures of merit are negative. Clearly, as used with the standard arrival and departure procedures built into the INM, the INM underpredicts sound levels for many of the aircraft / track distances examined.[9]

Suggestions that temperature, airport elevation, and departure procedures must be more realistically modeled have been briefly examined, and some improvement in the agreement between computed and measured levels is possible. Though the exact flight procedures used for departures (and arrivals) can affect the sound levels produced in the community, as can temperature and airport elevation, these effects are either small or likely to be confined to areas within about 40,000 feet of brake release, (or within about 6 miles of the airport). The analyses presented in this report for both Denver and MSP show that the differences between computed and measured SEL continue beyond this distance, with computed values consistently lower than measured values (negative figures of merit) by 3 to 5 dB for most aircraft types, for most track distances. Thus, though modeling exactly the procedures, temperatures and airport elevations may improve agreement between computed and measured results, these factors alone are unlikely to bring the figures of merit close to zero across all track distances for all aircraft types.

It has been suggested that use of stage length as a surrogate for aircraft take-off weight will tend to underestimate actual take-off weights. An analysis of the MSP data was conducted using the highest takeoff weights (longest stage lengths) available within the INM, rather than the takeoff weights assumed for the actual stage lengths flown (stage length 1 for MSP). Figures 76 through 83 summarizes the results for the eight different MSP aircraft analyzed. The dashed line in each figure shows the figures of merit for the maximum take-off weight (longest stage length), while the solid lines shows the results for the lighter take-off weight (stage length 1). The higher take-off weights increase the computed sound levels on the ground (aircraft climb more slowly and use greater thrust), and hence the difference between computed and measured SEL becomes more positive. If increasing modeled takeoff weight changes a figure of merit from negative (under prediction) to positive (over prediction) then possibly proper modeling of takeoff weight is sufficient to bring the figures of merit close to zero. Examination of Figures 76 through 83 shows that for less than half of the aircraft type / track distance combinations does the increase to maximum takeoff weight cause such a change in the figure of merit. Hence, for more than half the figures of merit analyzed, use of maximum takeoff weights is not sufficient to bring computed and measured values into close agreement. Other factors need investigation.

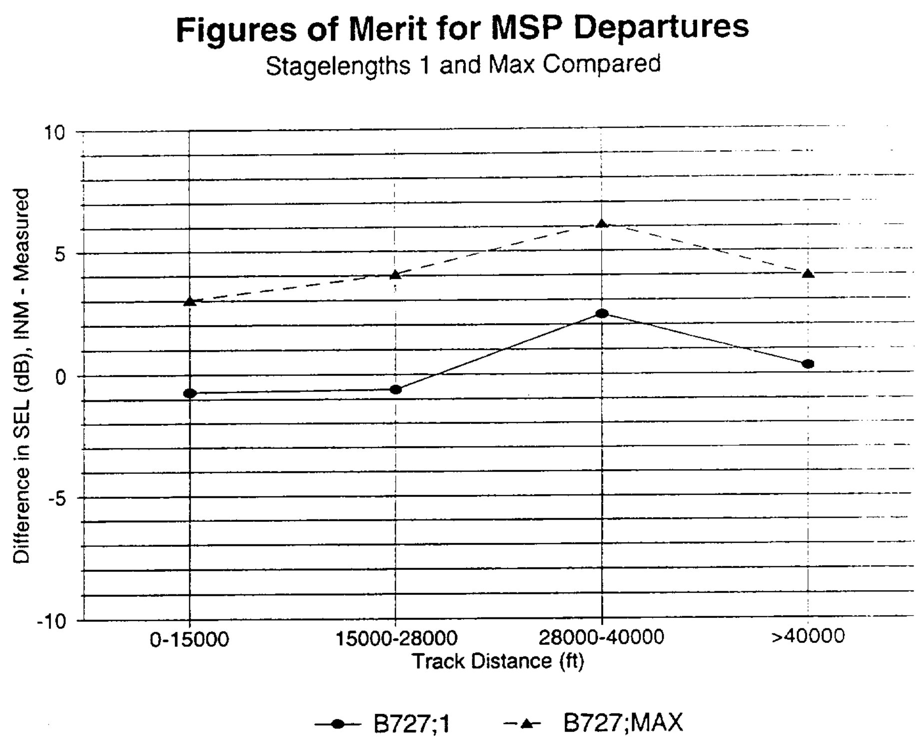

Figure 76. Effect of Takeoff Weight on Figures of Merit - B727

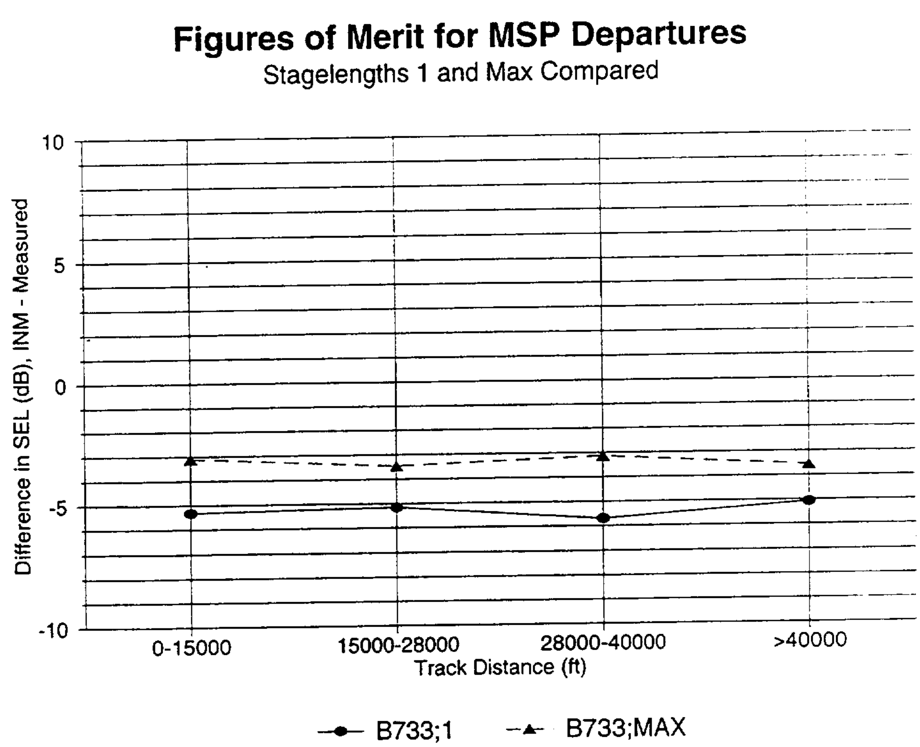

Figure 77. Effect of Takeoff Weight on Figures of Merit - B733

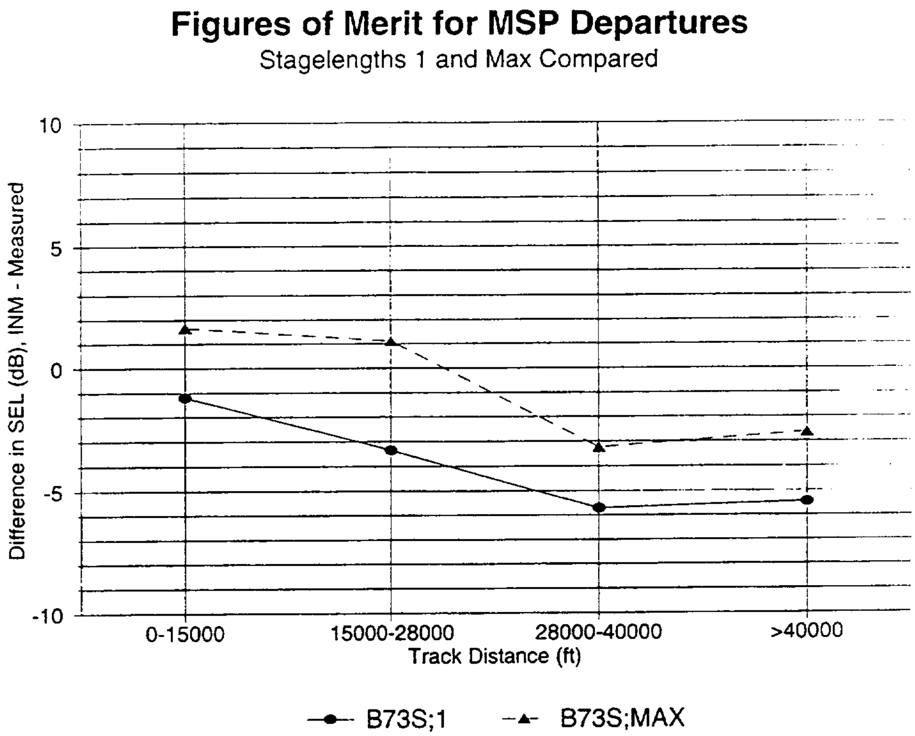

Figure 78. Effect of Takeoff Weight on Figures of Merit - B73S

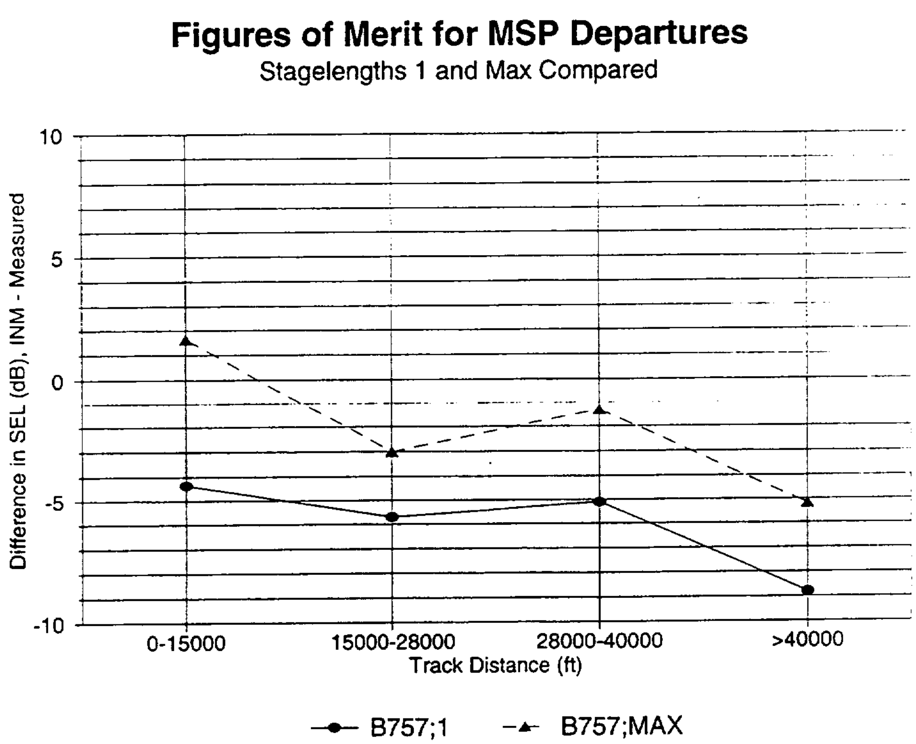

Figure 79. Effect of Takeoff Weight on Figures of Merit - B757

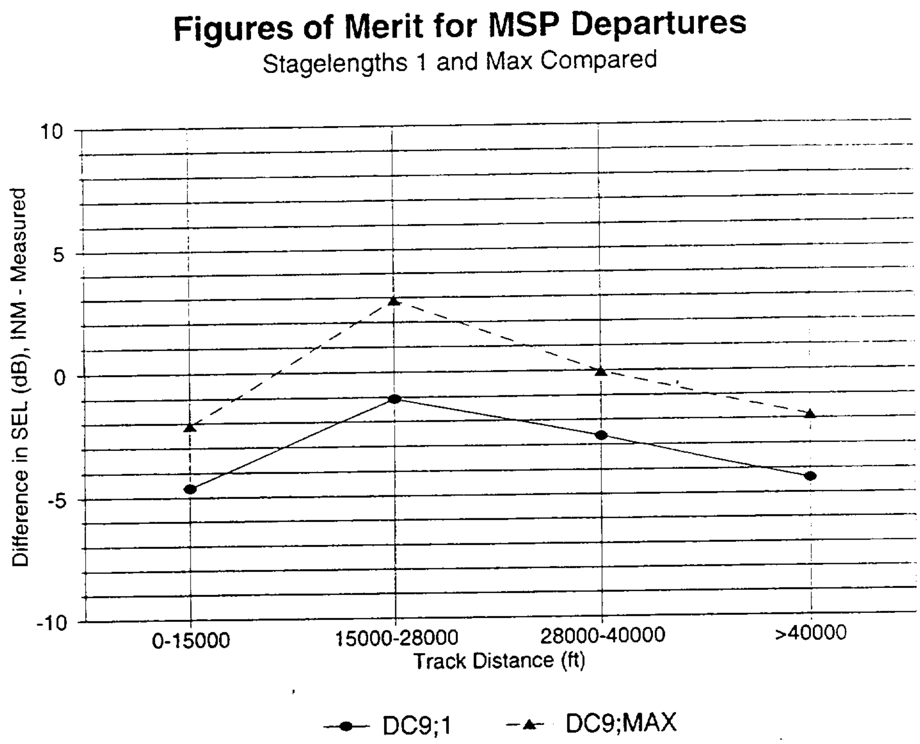

Figure 80. Effect of Takeoff Weight on Figures of Merit - DC9

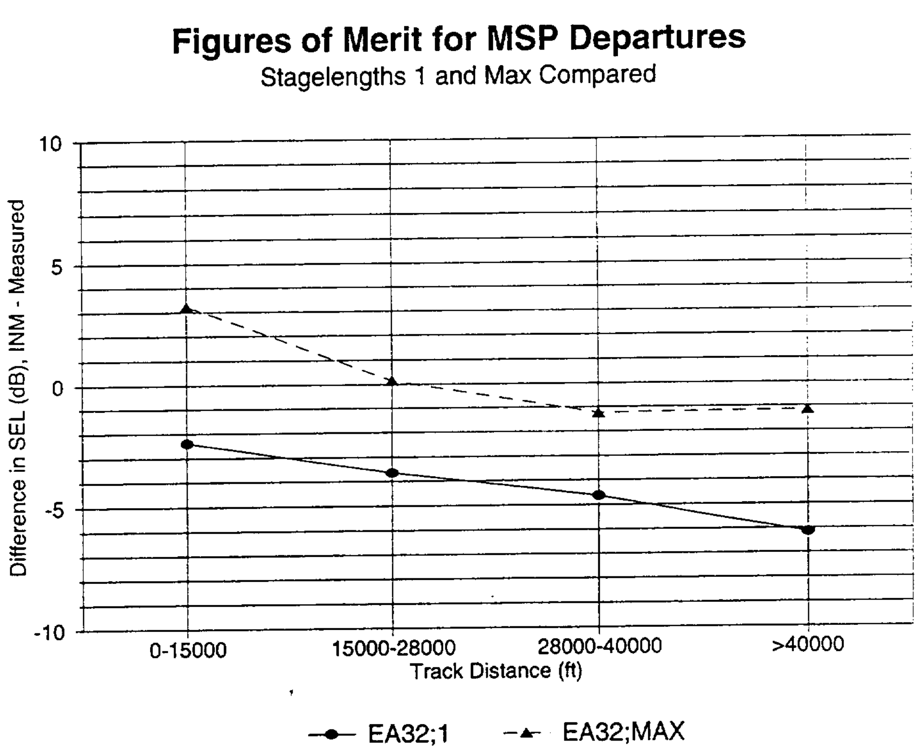

Figure 81. Effect of Takeoff Weight on Figures of Merit - EA32

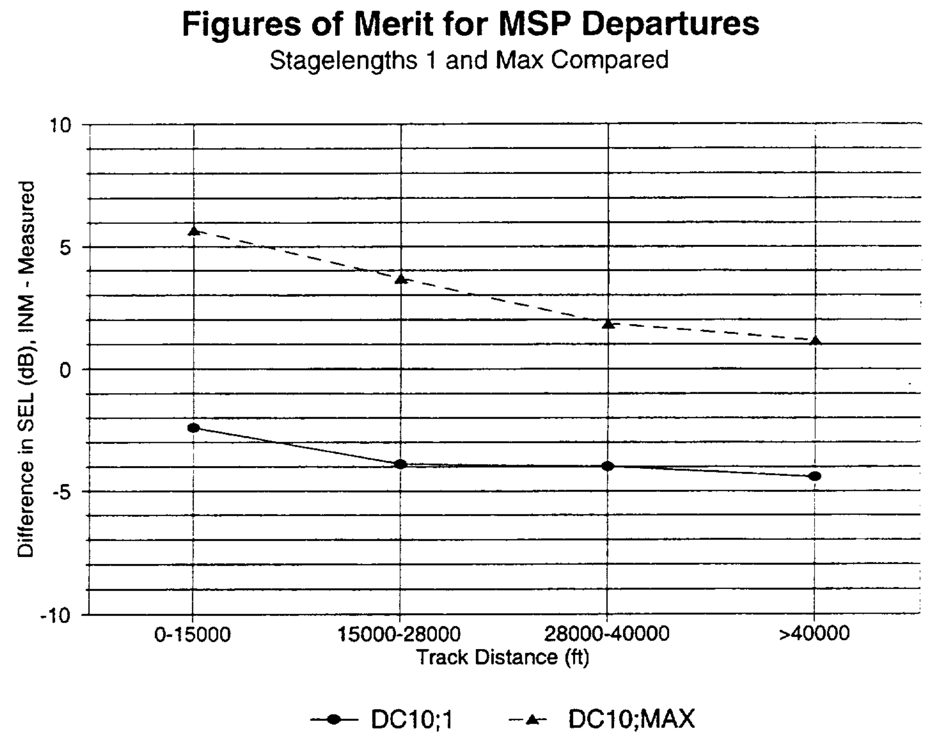

Figure 82. Effect of Takeoff Weight on Figures of Merit - DC10

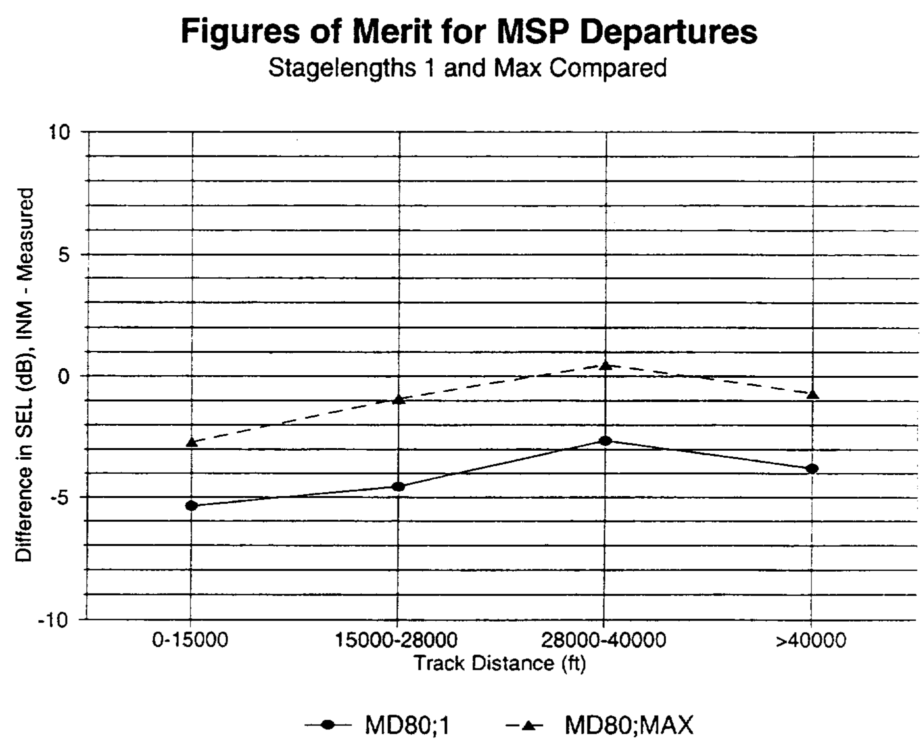

Figure 83. Effect of Takeoff Weight on Figures of Merit - MD80

7.2 Recommendations

Two key issues that should be investigated next include:

1. Changes in noise levels as a function of distance. Measured rates of change should be compared with those predicted by the INM. The analysis should differentiate between air-to-ground propagation and "lateral attenuation" when aircraft are at lower angles of elevation relative to the observer. The consistently negative figures of merit may be due, in part, to use of propagation rates derived originally from low-bypass, stage 1 and stage 2 aircraft[10]. Both the MSP and Denver data can provide a means for examining the empirical propagation rates for several aircraft types.

2. Ability of the INM to accurately compute SEL as measured during certification tests. Several certification tests of each of several aircraft types should be modeled, including 737-300/400/500, 757, EA32, MD80. The issues of the importance of accurately modeling the flight procedures, takeoff weights, thrusts and speeds can be addressed by using the INM to model certification tests. The fundamental question to be answered is: When an aircraft departure is modeled using the actual thrust, weight, speed, altitude, aircraft model / engine type, how closely do computed results match the measured results?

Investigation of these two issues will address INM accuracy at a reasonable next level of detail, and for locations both close to and far from the airport. Propagation analysis addresses the accuracy of the INM at larger track / slant distances. Modeling the certification tests will demonstrate INM accuracy under best-case conditions: short slant distances, standard atmospheric conditions, known engine type, known thrust / speed / altitude.

Errors in propagation (at least air-to-ground propagation) should have minimal effects close to the airport, but could be significant as aircraft climb higher and thus if corrected may improve computed / measured agreement at the longer track distances. Modeling the certification tests will reveal, for the modeled aircraft types, the greatest accuracy of which the INM is capable.

Taken together, these two investigations will help define further areas for analysis. Table 15 suggests possible directions, depending upon the results of the suggested analyses of these two key issues. For example, if the INM modeling provides results that agree reasonably well with certification measurements, then one outcome would be to set up a method for including more realistic departure procedures in INM modeling. If the measured propagation rates are reasonably comparable to those assumed within the INM, then some other factor must be causing the differences at long propagation distances (at higher aircraft altitudes). One possible source of error that could be examined is the way in which corrected net thrust is associated with the noise generation of the engines.[11]

If INM modeling does not duplicate the certification measured sound levels, then it is important to analyze the derivation of the NPD (noise-power-distance) relationships from the certification data. The INM uses assumed or modeled departure procedures to determine aircraft climb rate and associated thrust. Climb rate determines where an aircraft is located in relation to the ground, and thrust (corrected net thrust) is used to determine the source level. Aircraft position is generally less critical than thrust in determining sound levels on the ground.

Finally, if INM propagation is significantly different from the empirical propagation, the appropriate theory needs to be reviewed, developed, tested and incorporated into the INM.

Table 14. Possible Directions for Further Analysis Depending upon Investigation of Key Issues

Modeling of Certification Tests	Propagation Analyses	
	INM Reasonable	INM Inaccurate
Model Agrees w/ Certification	1. Develop more realistic INM departure procedures 2. Examine how the use of "corrected net thrust" is associated with engine noise generation at other than standard conditions (higher altitudes)	1. Revise INM propagation 2. Develop more realistic INM departure procedures
Model Disagrees w/ Certification	1. Analysis of derivation of NPD's from certification data 2. Examine how the use of "corrected net thrust" is associated with engine noise generation at other than standard conditions (higher altitudes)	1. Revise INM Propagation 2. Analysis of derivation of NPD's from certification data

8. REFERENCES AND NOTES

1. Gados, R. G., and Aldred, J.M., "FAA Integrated Noise Model Phase I: Analysis of Integrated Noise Model Calculations for Air Carrier Flyovers," MITRE Report MTR-79W00095, December 1979, FAA Report No. FAA-EE-80-4.

2. Gados, R. G., "Comparison of FAA Integrated Noise Model Flight Profiles with Observed Altitudes and Velocities at Dulles Airport," MITRE Report MTR-80W00119, March 1980.

3. Flathers, G.W., "A Comparison of FAA Integrated Noise Model Flight Profiles with Profiles Observed at Seattle_Tacoma Airport," MITRE Report MTR-81W288, December 1981, FAA Report No. FAA-EE-82-10.

4. Flathers, G.W., "FAA Integrated Noise Model Validation: Analysis of Air Carrier Flyovers at Seattle_Tacoma Airport," MITRE Report MTR-82W162, FAA Report No. FAA-EE-82-19.

5. Page, J.A., *et al*, "Validation of Aircraft Noise Models at Lower Levels of Exposure," (draft) Wyle Research Report WR 96-11, February, 1996.

6. STATISTICA© for Windows by StatSoft, Inc. was used for all analysis.

7. The assumptions of SAE Aerospace Information Report 1751 are currently being examined and likely will ultimately be revised. The effort is to develop the "lateral attenuation" algorithms from a more theoretical basis to include the effects of reflection from the ground plane and the effects of reflections or shielding from the airframe as a function of type / location of engine mounting.

8. These points resulted from arrival tracks that have long downwind segments with an RMT located so that two points of closest approach result - one relative to the downwind, one relative to the final. The INM reported only the results for the final, despite the downwind being closer to the RMT. Hence, the measured levels include the values generated by the downwind, while the INM results apparently include only the information (altitude, track distance, SEL) generated by the final. The points of Figure 32 are at high altitudes because ANOMS is reporting the downwind altitude, while the track distance is from the INM, which is reporting the information for the PCA on the final. This shortcoming has been reported to FAA.

9. It should be noted, as described in Section 4.2.2, that all analyses and the determinations of figures of merit in this report are based on sound level data for situations when the aircraft, as modeled, are 60 degrees or more above the horizon relative to the measurement / prediction location. Limiting the analyses to these data insured that the propagation effects of ground reflections, shielding and temperature / wind gradients were removed or of limited influence on the comparisons of computed and measured levels.

10. SAE Aerospace Information Report 1751, "Prediction Method for Lateral Attenuation of Airplane Noise during Takeoff and Landing" from which INM lateral attenuation was derived is under review for improvements.

11. Currently, it is our understanding that the relationship of corrected net thrust to noise produced is based upon measurements made at lower altitudes and at close to standard day conditions. If propagation assumed within the INM is close to the empirical (air to ground) propagation, a reasonable starting point for further investigation is this thrust / noise relationship as a function of altitude.

Appendix A

Comparison of Calculated and Measured SEL Data
Six Aircraft Types

List of Figures

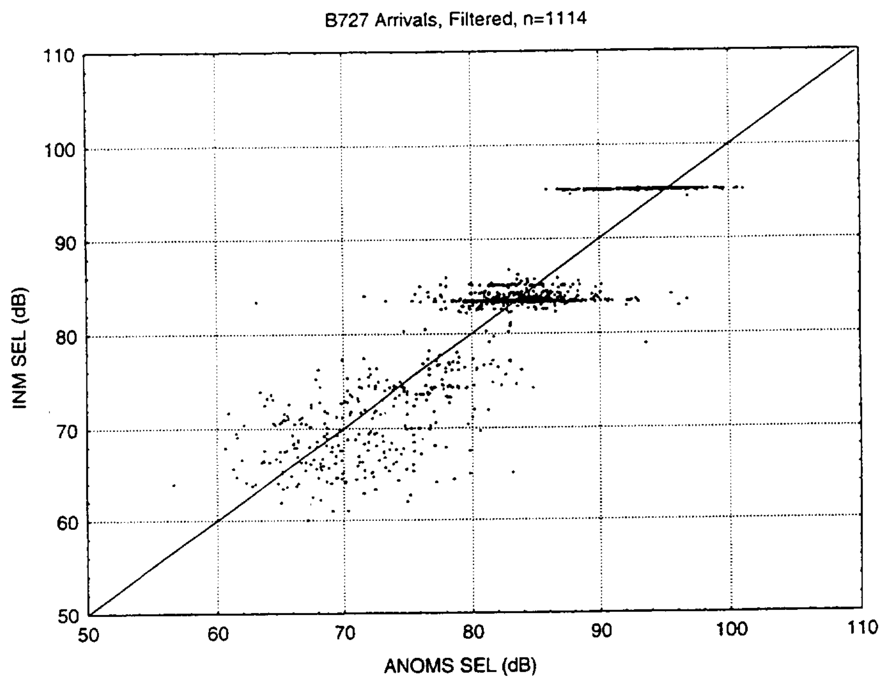

Figure A1. Calculated versus Computed SEL - B727 Arrivals

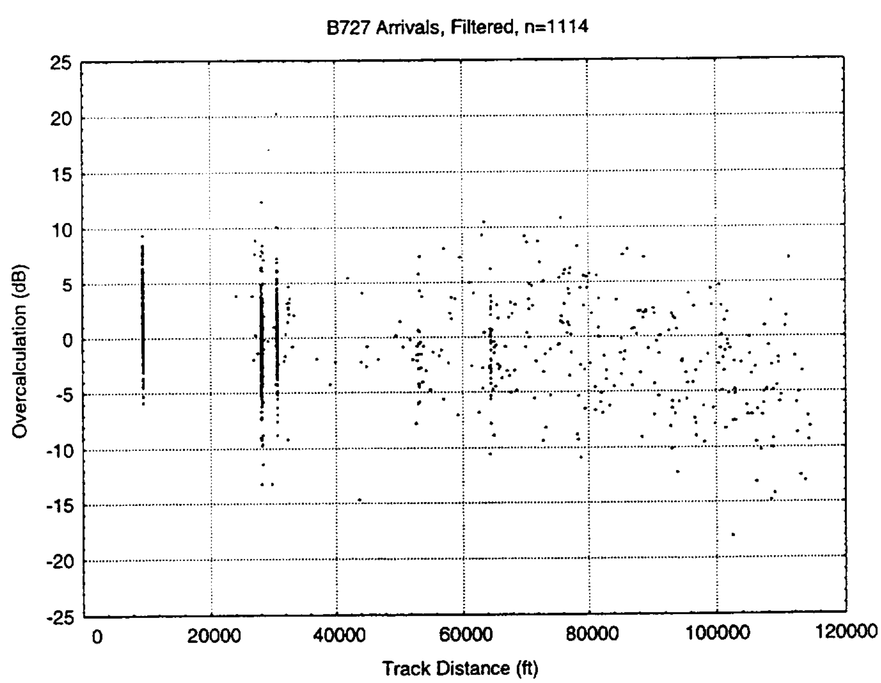

Figure A2. Difference in SEL versus Track Distance - B727 Arrivals

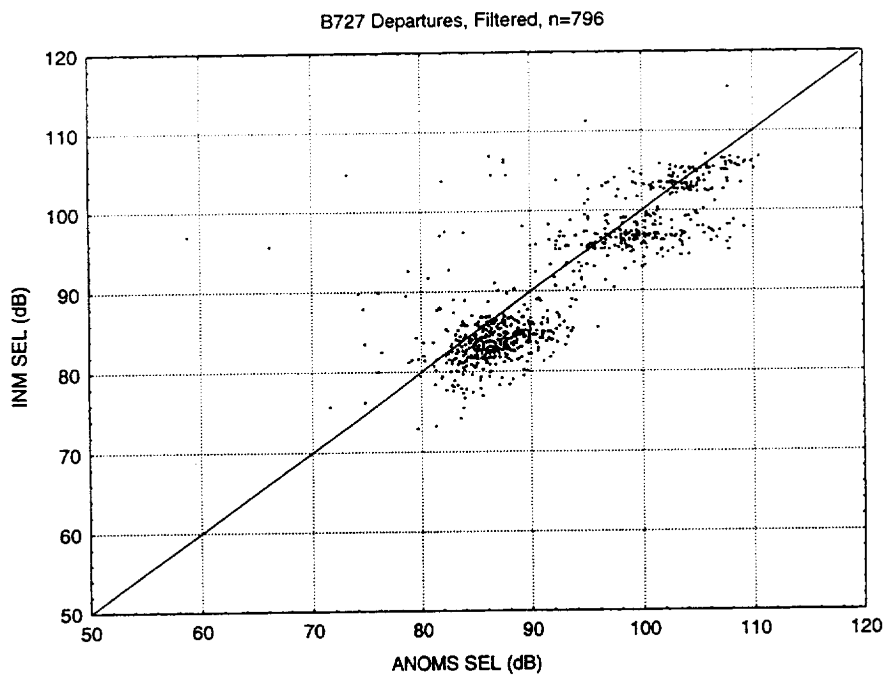

Figure A3. Calculated versus Computed SEL - B727 Departures

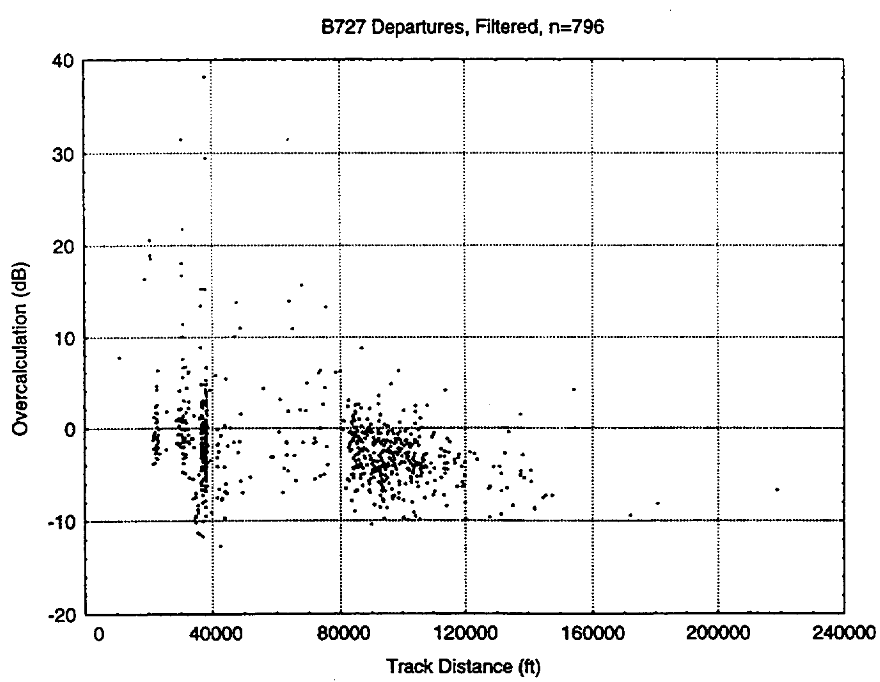

Figure A4. Difference in SEL versus Track Distance - B727 Departures

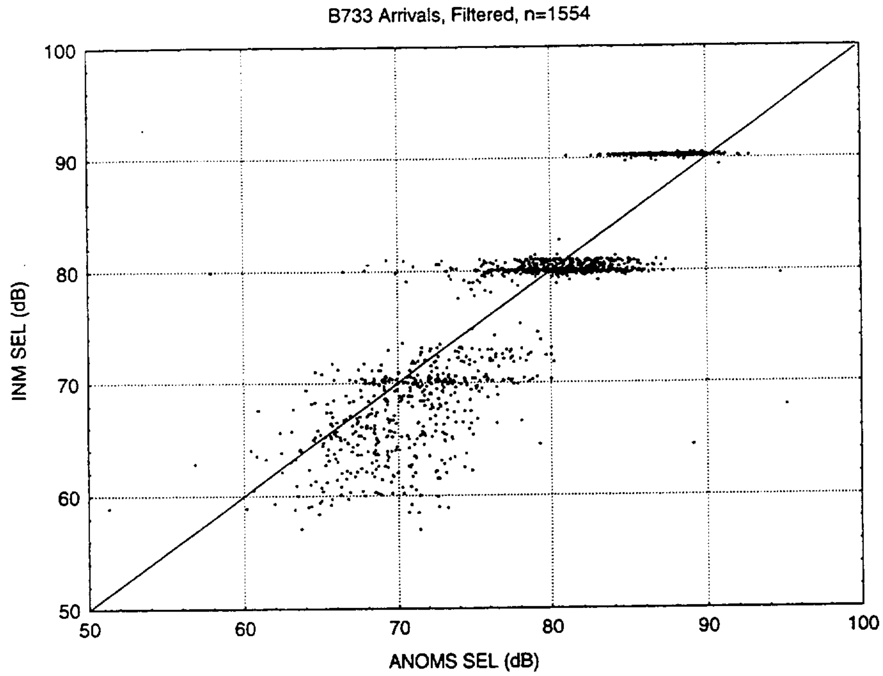

Figure A5. Calculated versus Computed SEL - B733 Arrivals

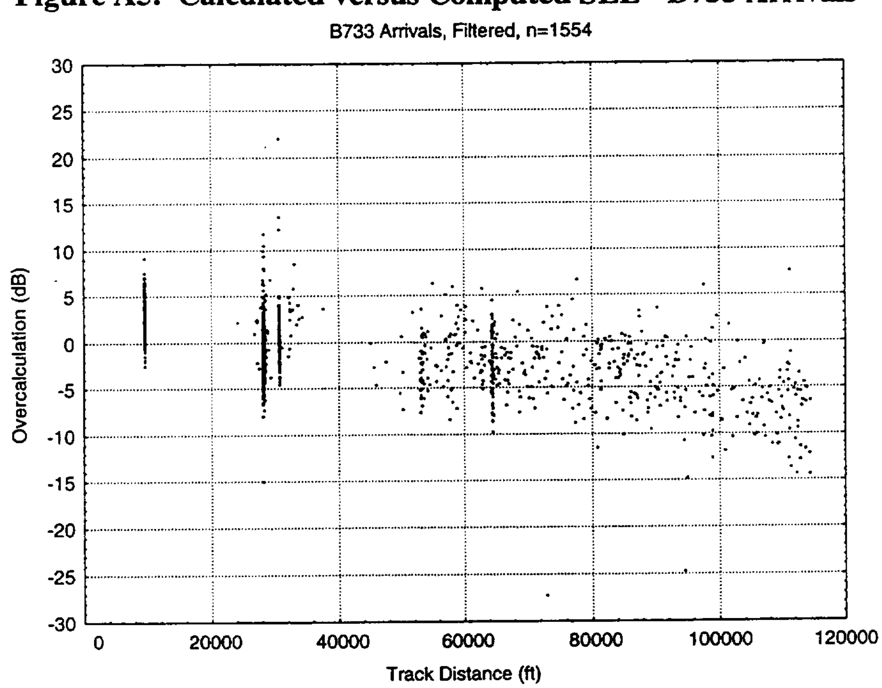

Figure A6. Difference in SEL versus Track Distance - B733 Arrivals

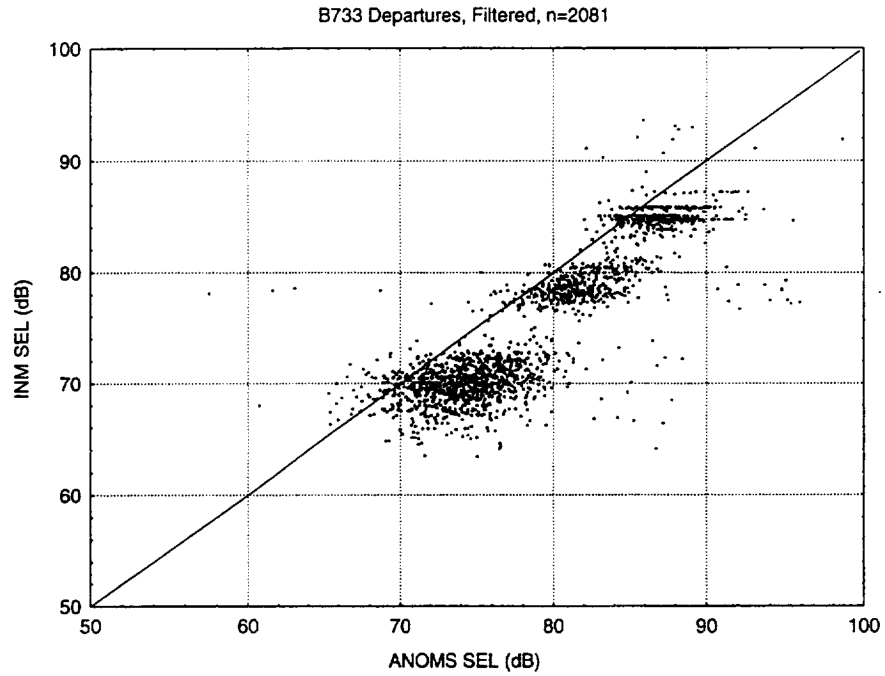

Figure A7. Calculated versus Computed SEL - B733 Departures

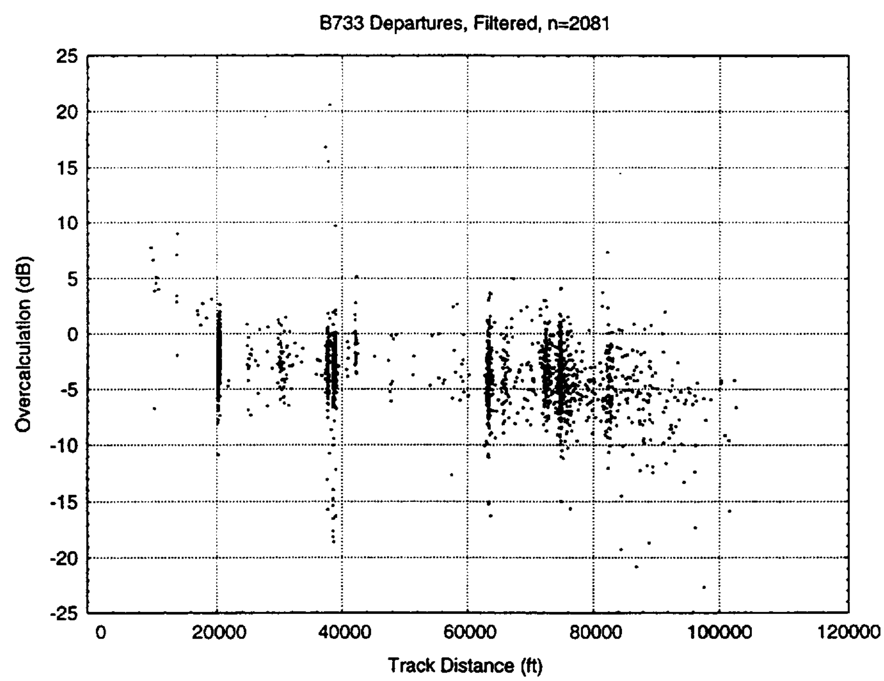

Figure A8. Difference in SEL versus Track Distance - B733 Departures

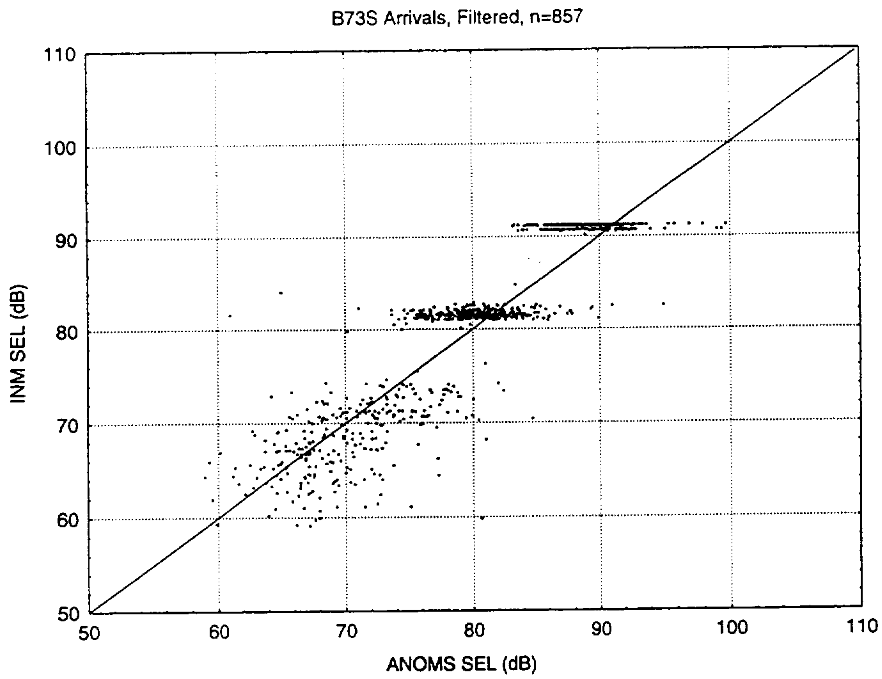

Figure A9. Calculated versus Computed SEL - B73S Arrivals

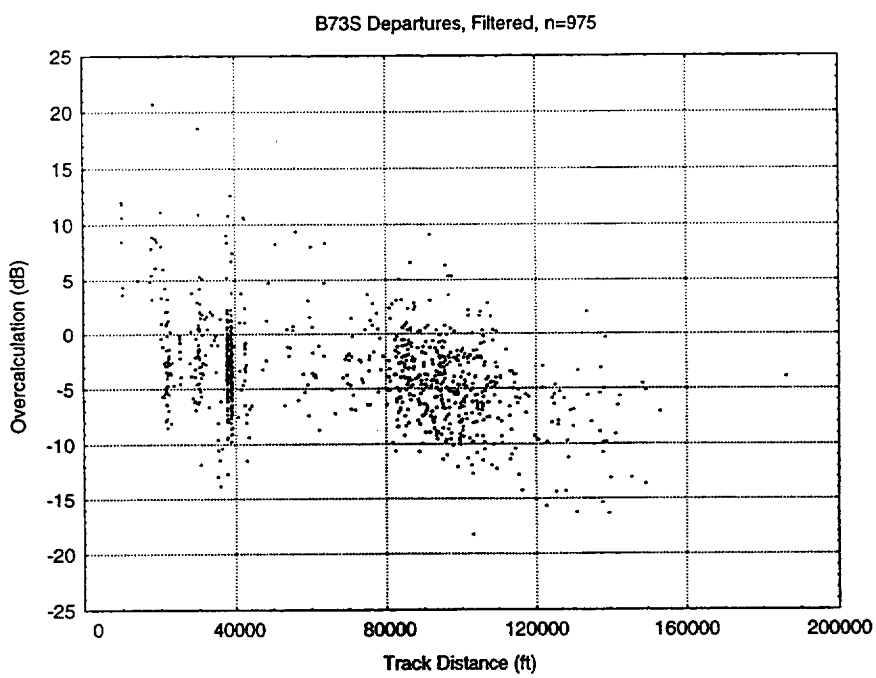

Figure A10. Difference in SEL versus Track Distance - B73S Arrivals

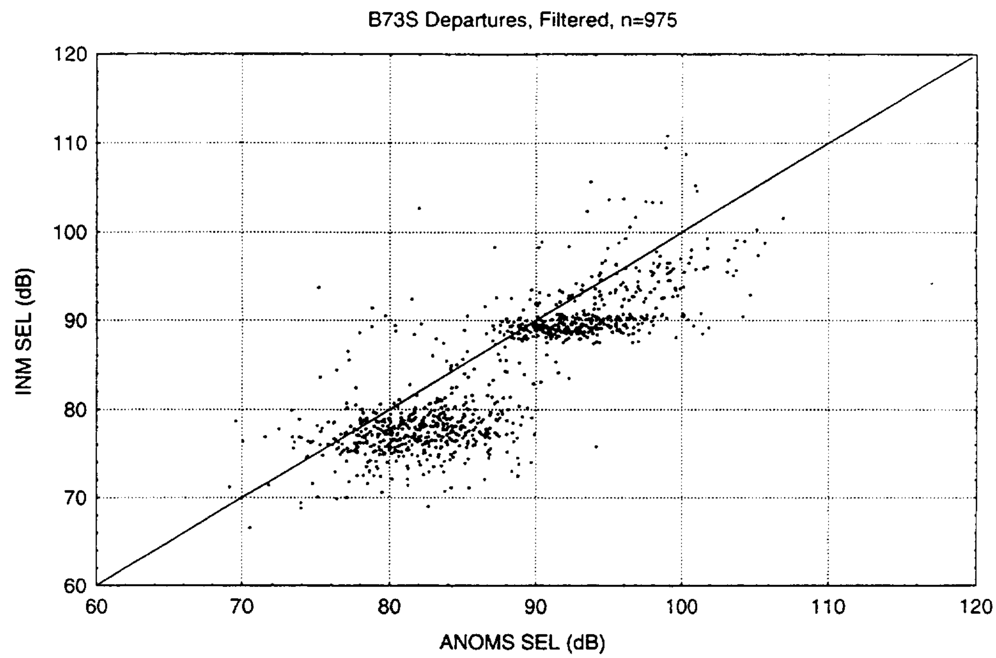

Figure A11. Calculated versus Computed SEL - B73S Departures

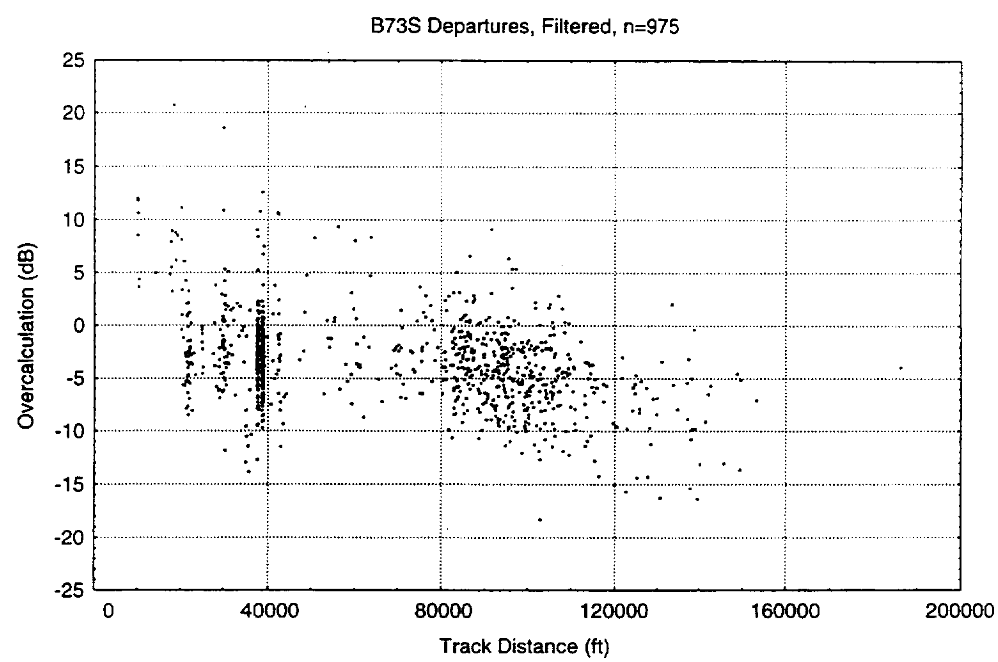

Figure A12. Difference in SEL versus Track Distance - B73S Departures

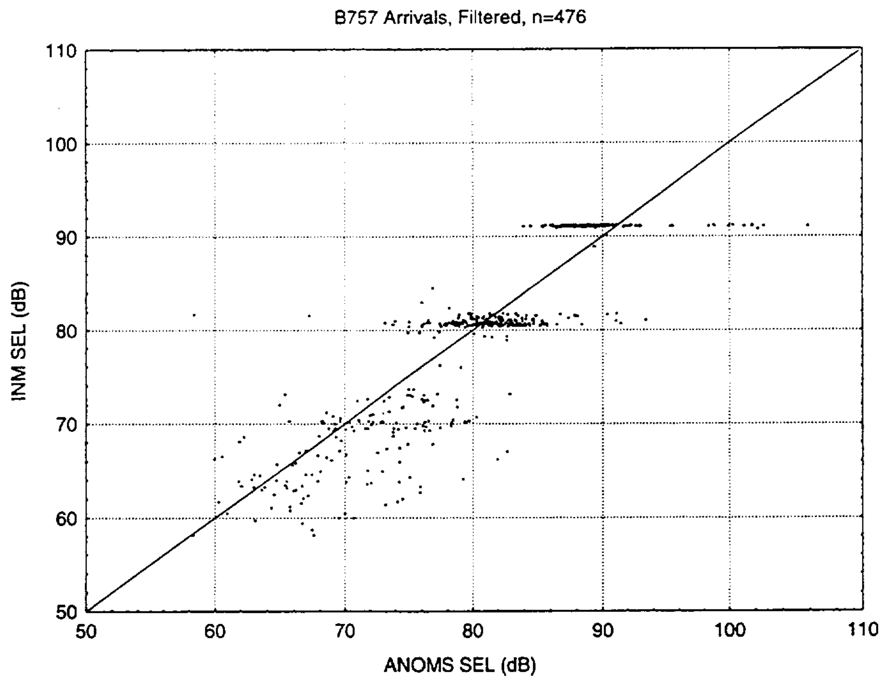

Figure A13. Calculated versus Computed SEL - B757 Arrivals

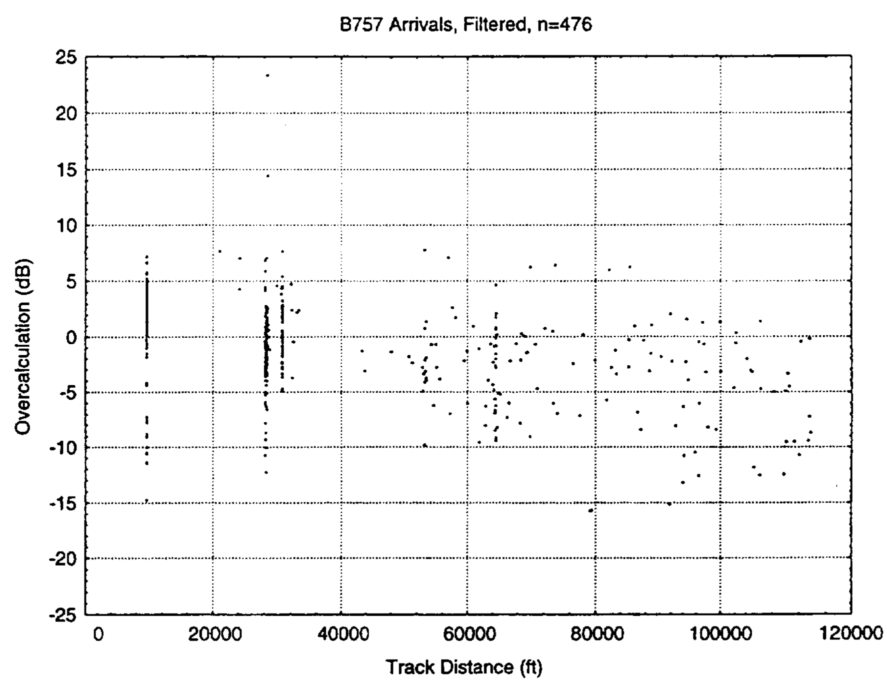

Figure A14. Difference in SEL versus Track Distance - B757 Arrivals

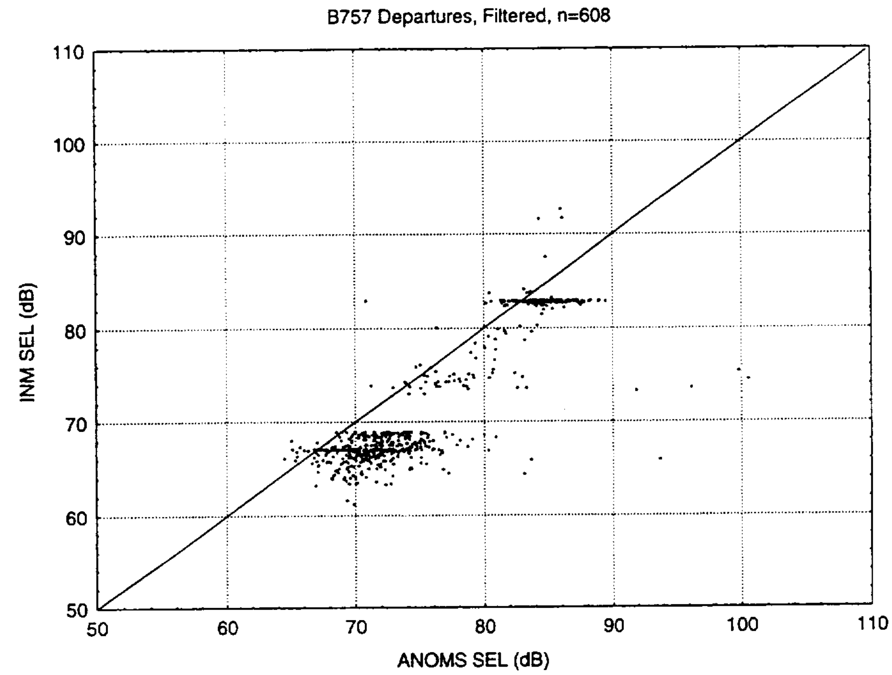

Figure A15. Calculated versus Computed SEL - B757 Departures

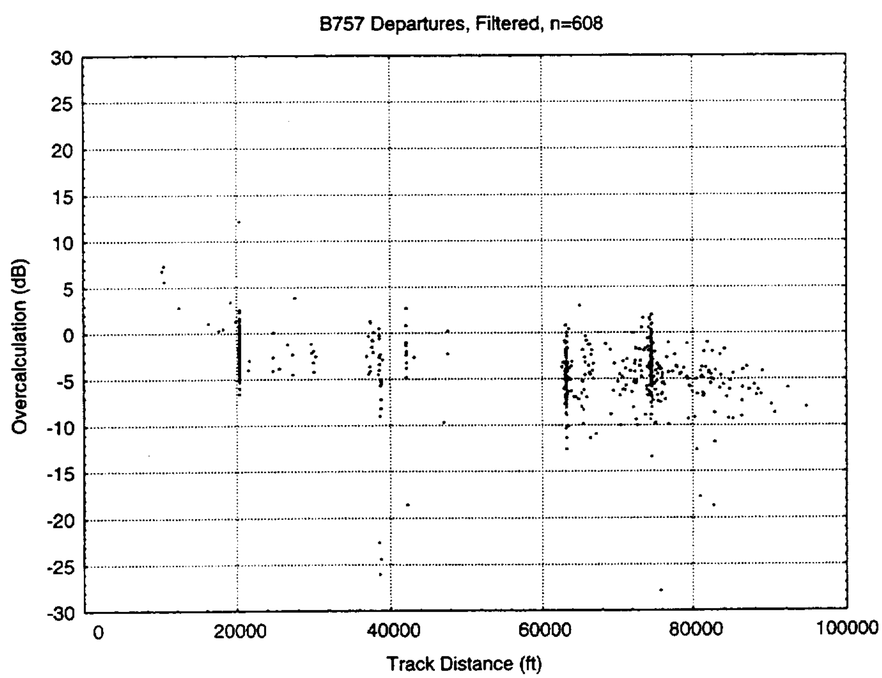

Figure A16. Difference in SEL versus Track Distance - B757 Departures

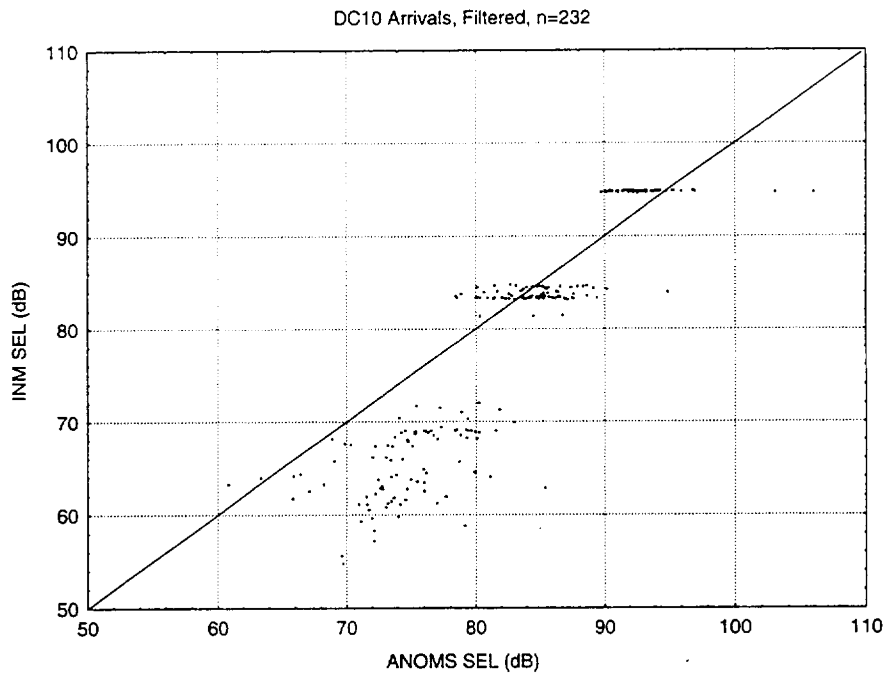

Figure A17. Calculated versus Computed SEL - DC10 Arrivals

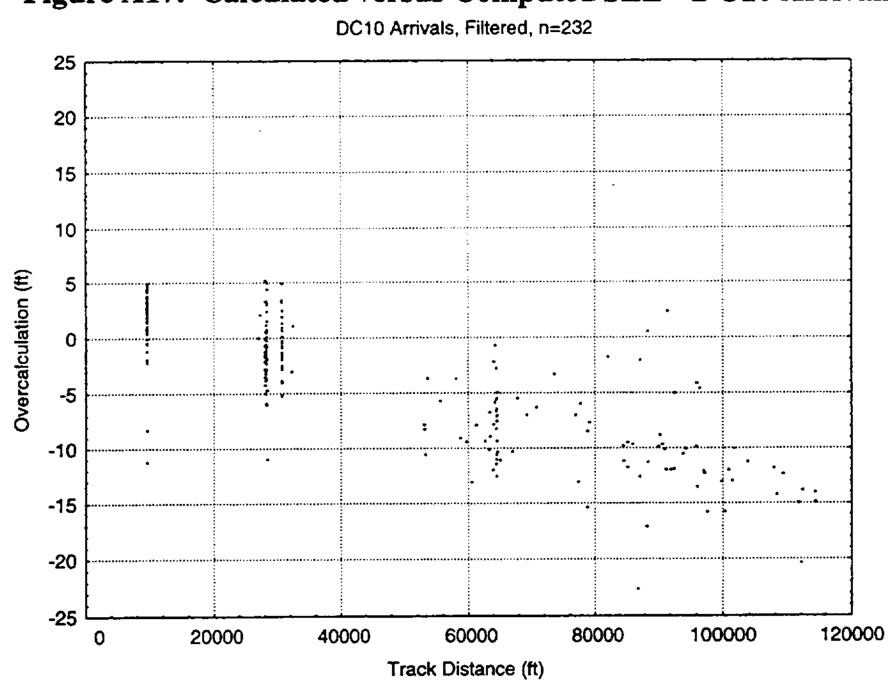

Figure A18. Difference in SEL versus Track Distance - DC10 Arrivals

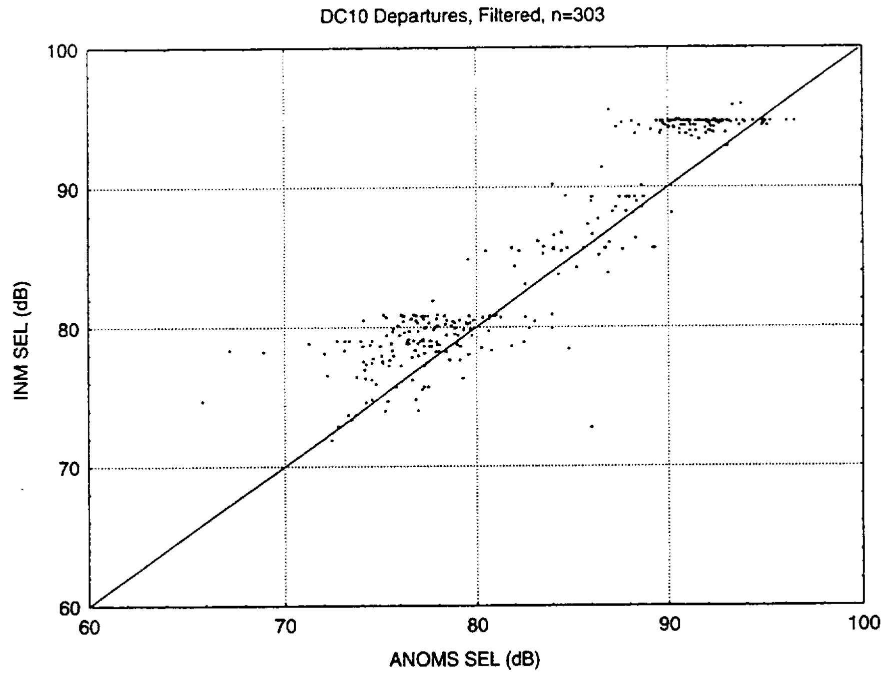

Figure A19. Calculated versus Computed SEL - DC10 Departures

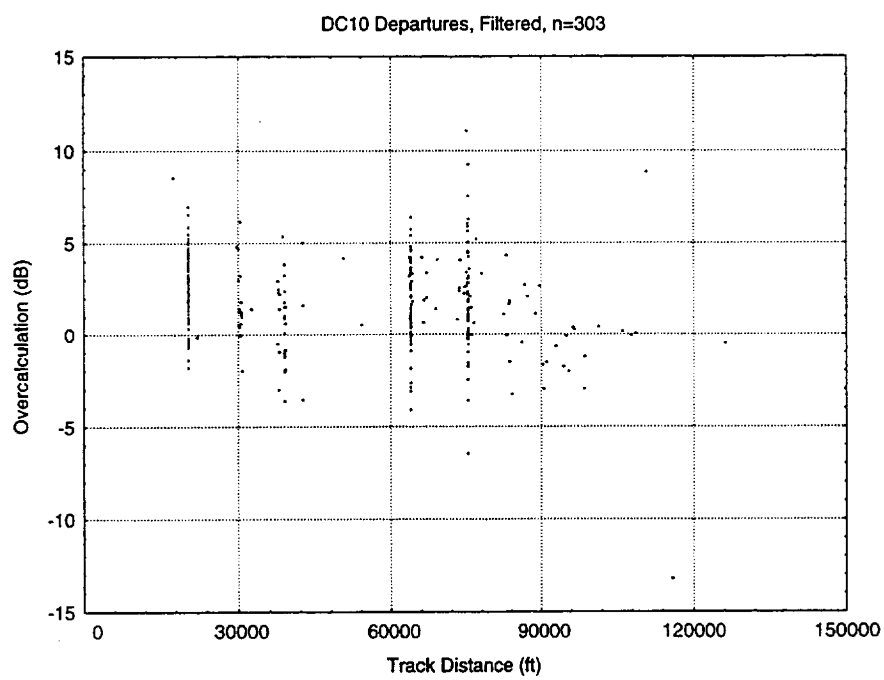

Figure A20. Difference in SEL versus Track Distance - DC10 Departures

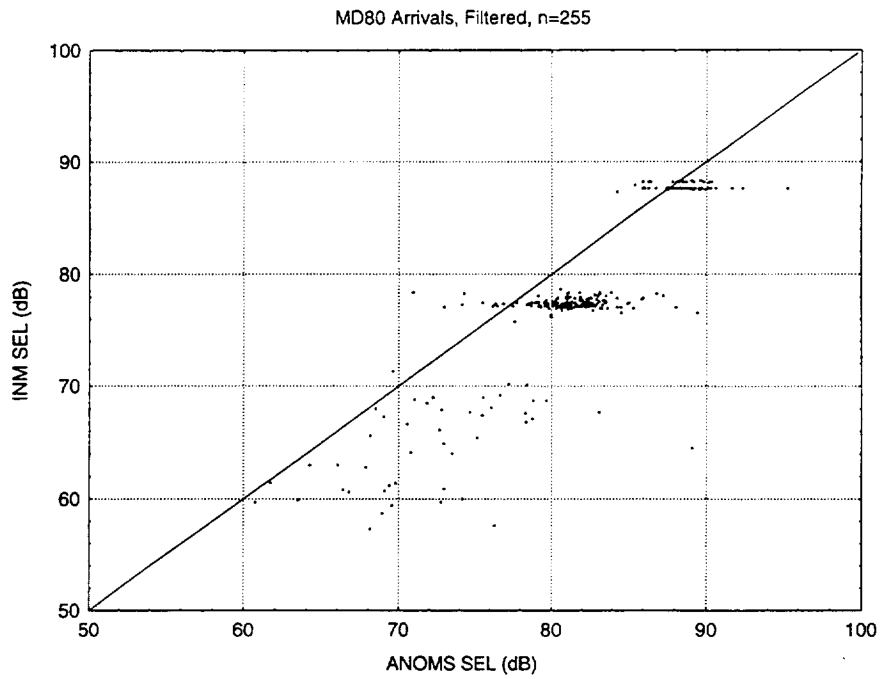

Figure A21. Calculated versus Computed SEL - MD80 Arrivals

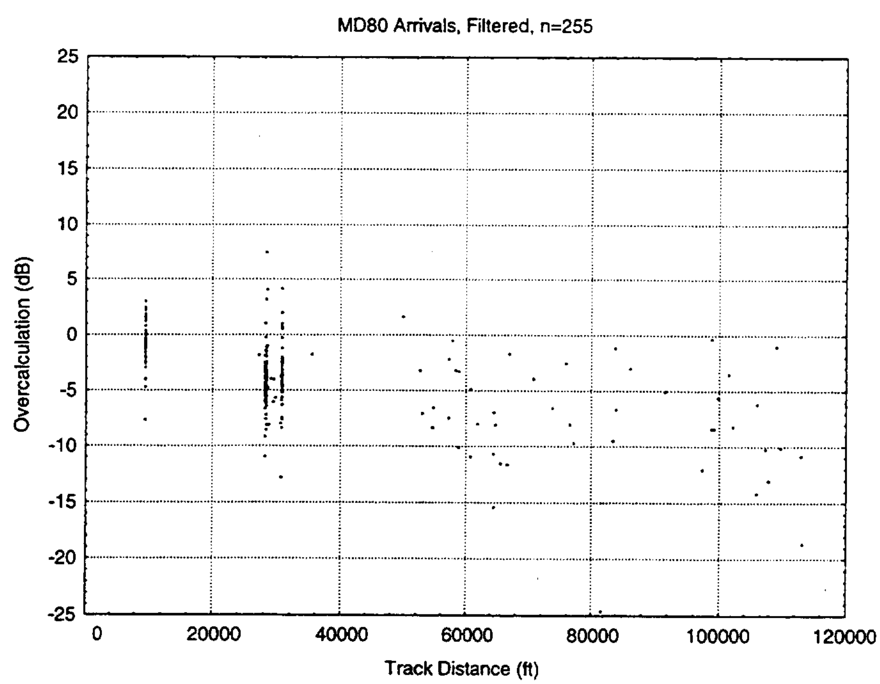

Figure A22. Difference in SEL versus Track Distance - MD80 Arrivals

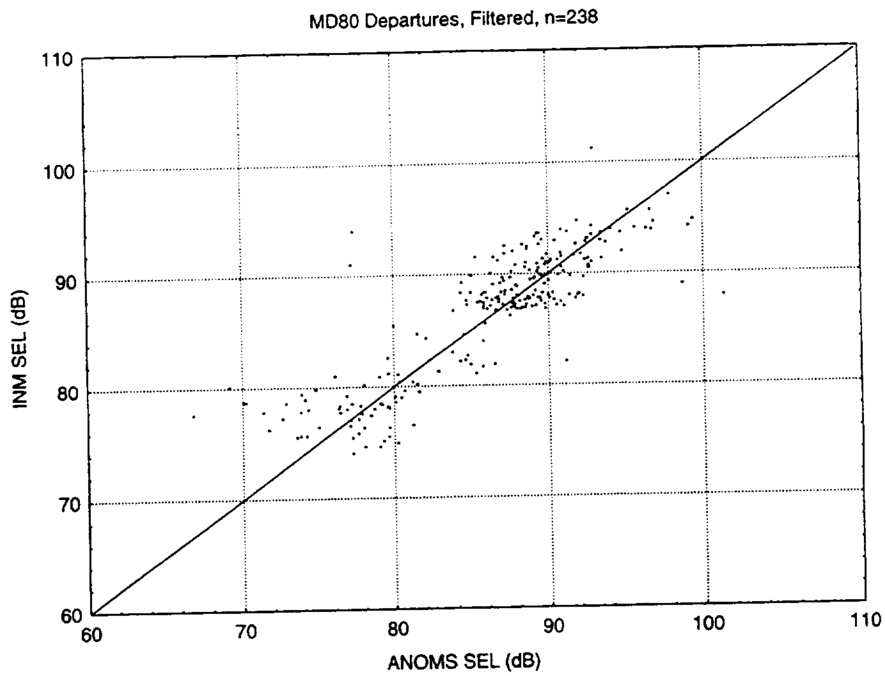

Figure A23. Calculated versus Computed SEL - MD80 Departures

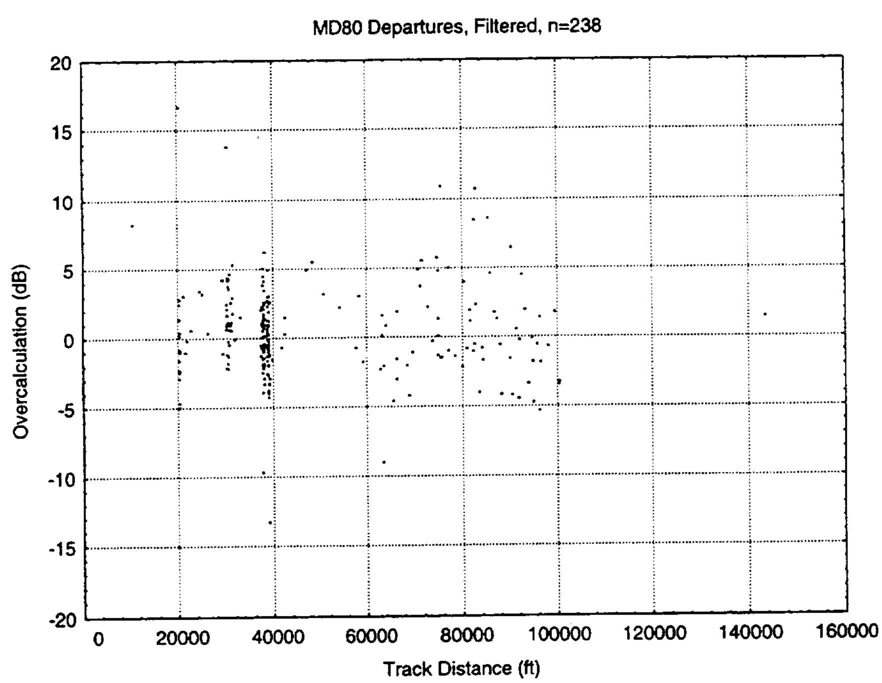

Figure A24. Difference in SEL versus Track Distance - MD80 Departures

Appendix B

Altitude Profiles
Six Aircraft Types

List of Figures

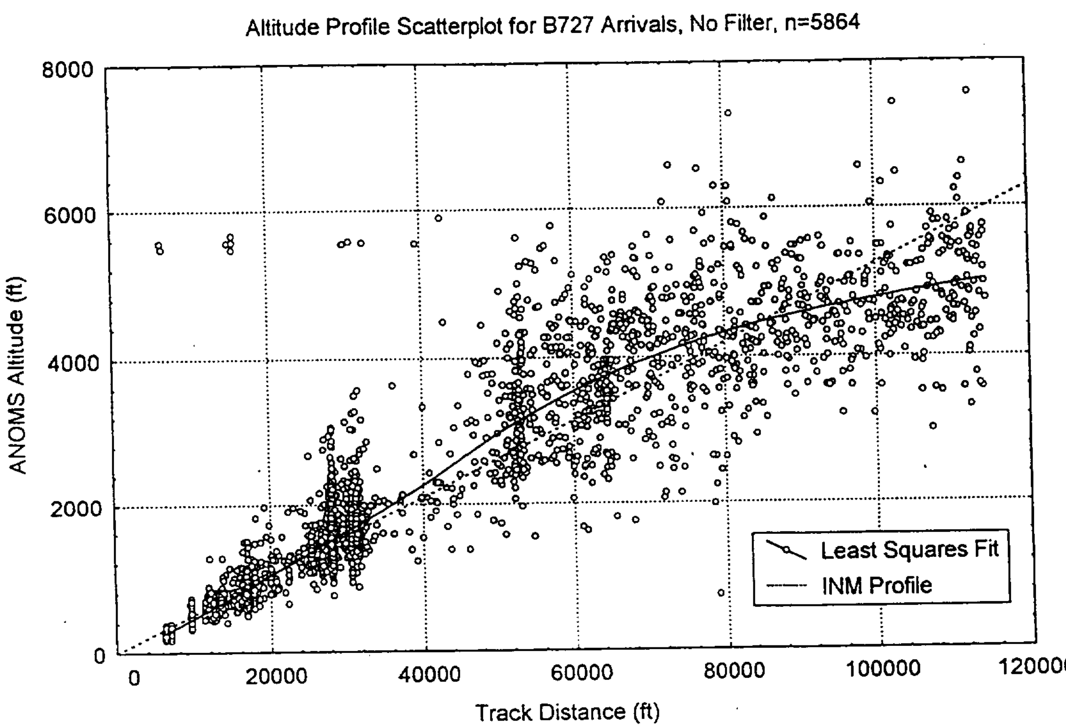

Figure B1. Arrival Altitudes: Measured, Least Squares, INM - B727

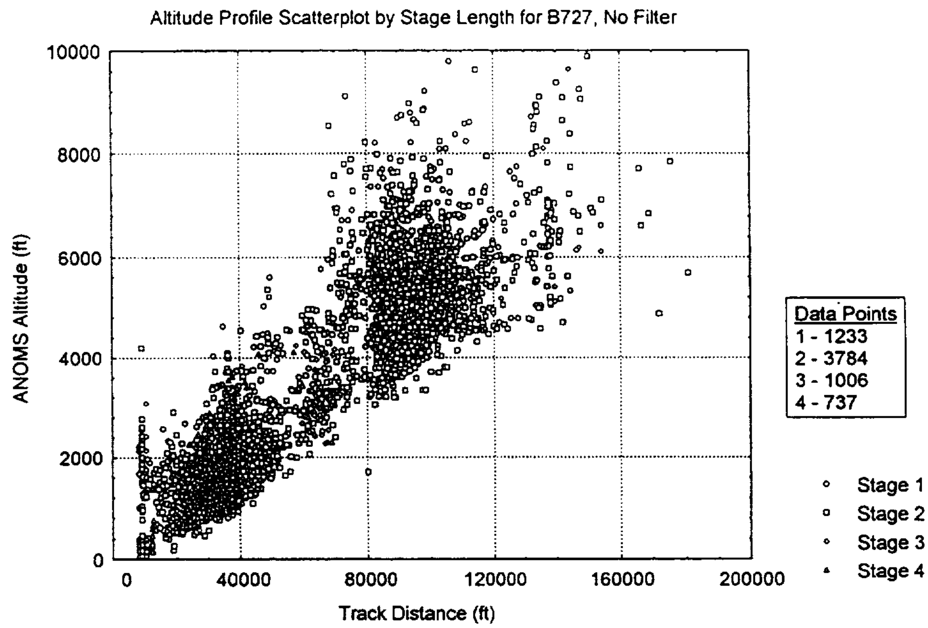

Figure B2. Departure Altitudes: Measured by Stage Length - B727

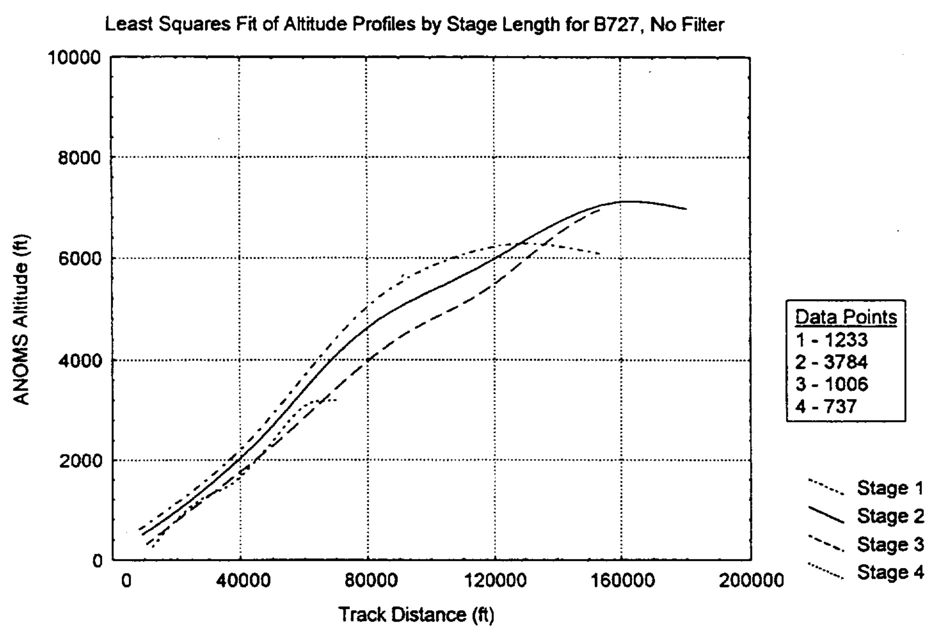

Figure B3. Departure Altitudes: Least Squares - B727

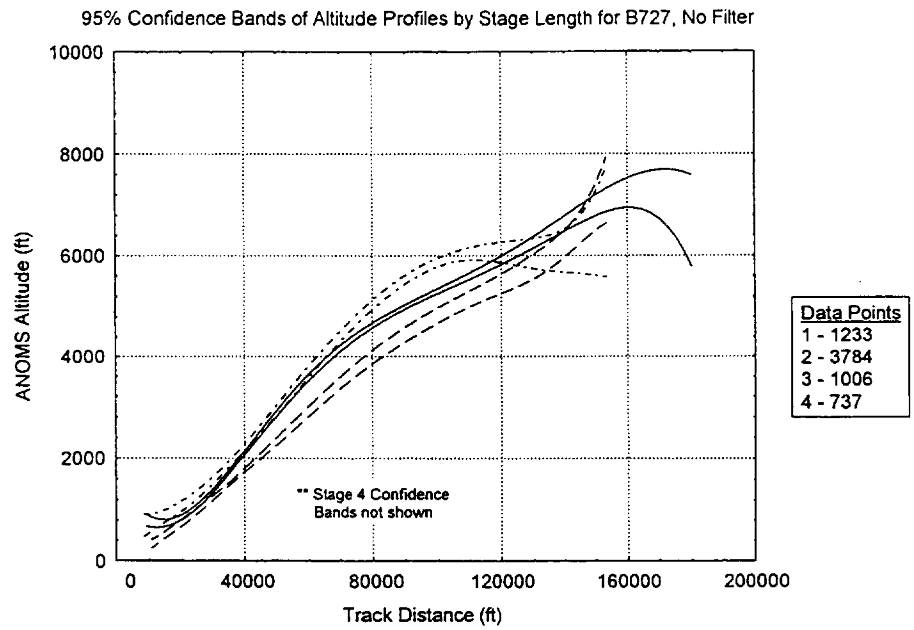

Figure B4. Departure Altitudes: Confidence Limits - 727

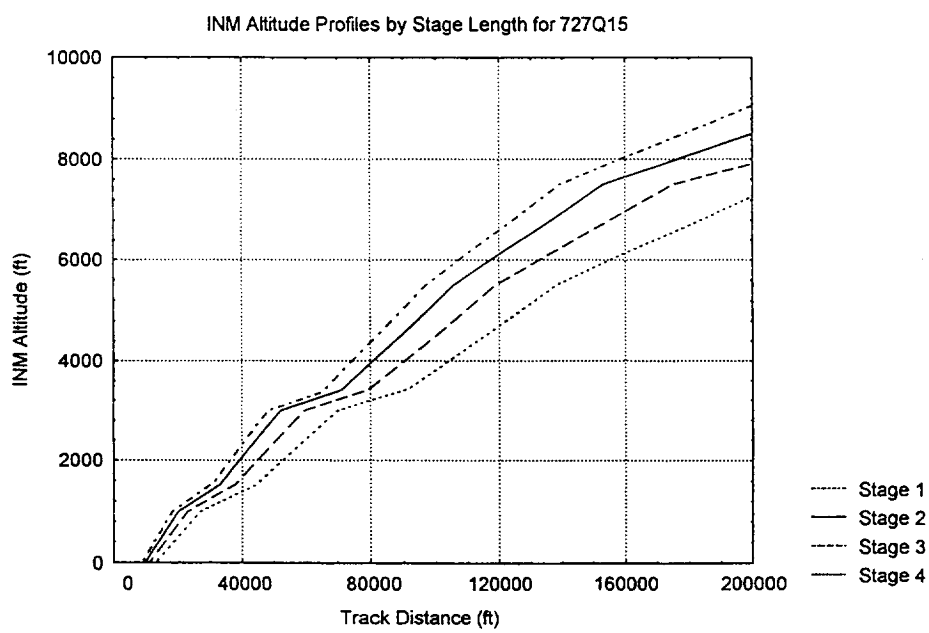

Figure B5. Departure Altitudes: INM - 727Q15

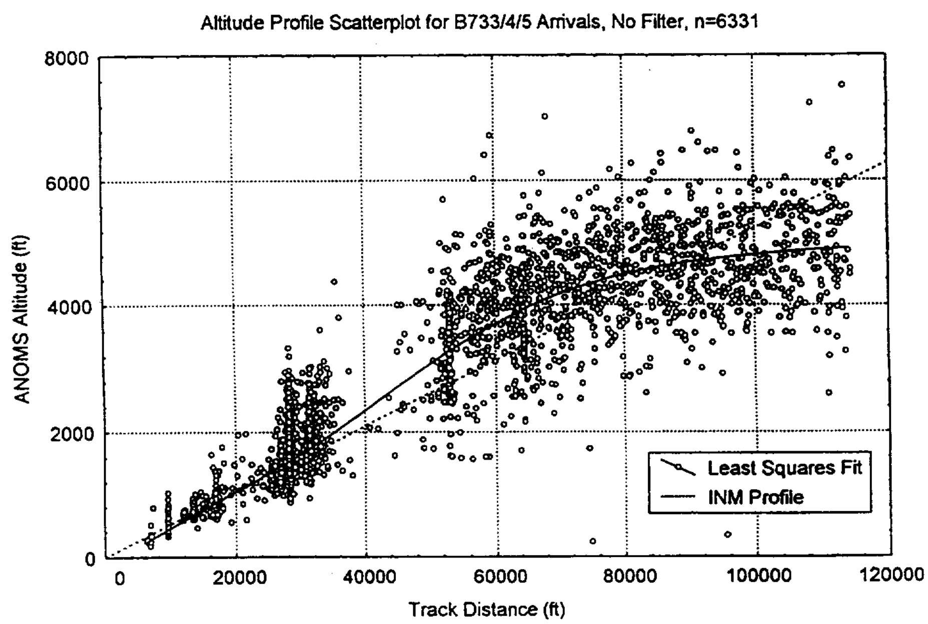

Figure B6. Arrival Altitudes: Measured, Least Squares, INM - B733/4/5

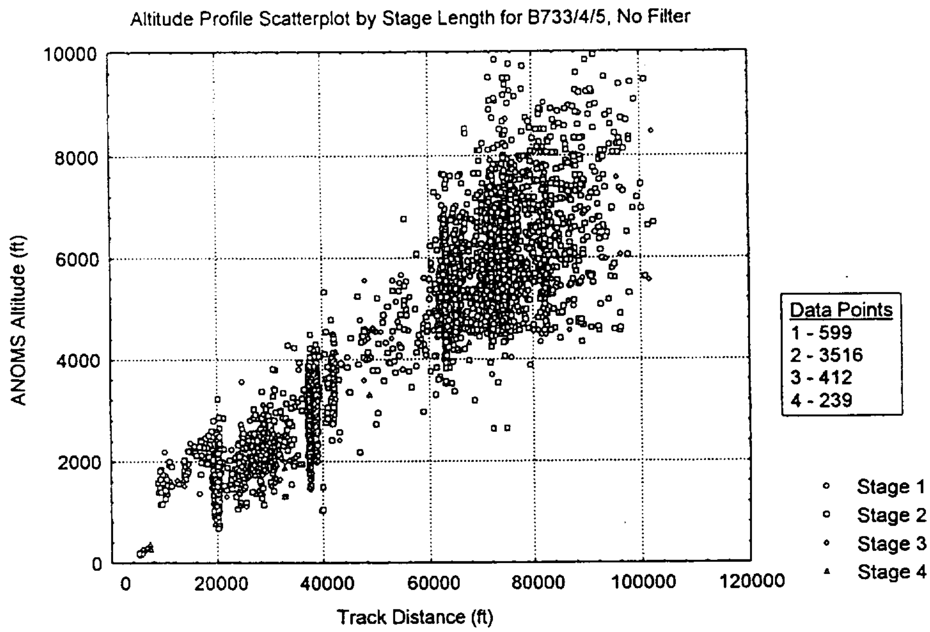

Figure B7. Departure Altitudes: Measured by Stage Length - B733/4/5

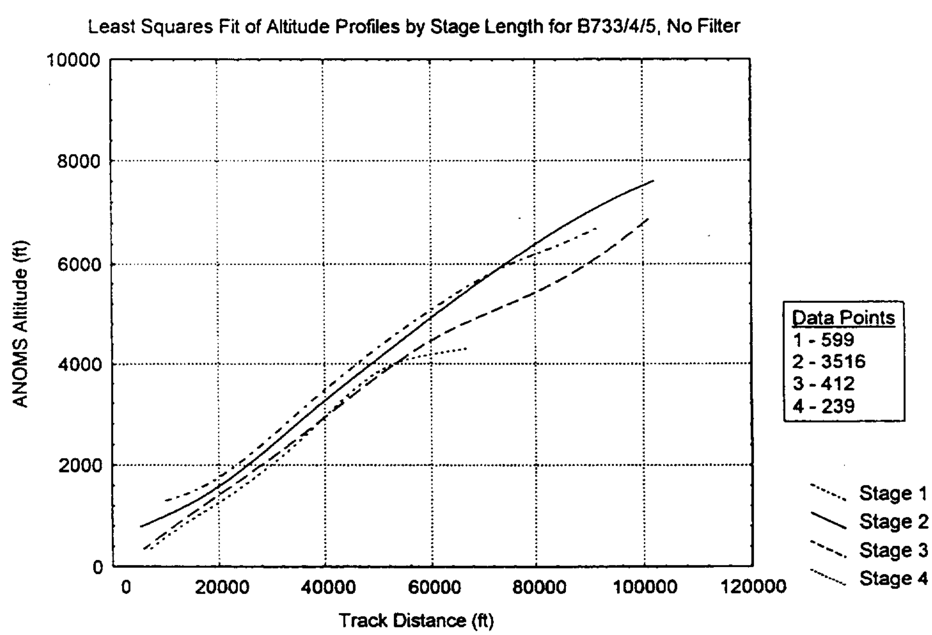

Figure B8. Departure Altitudes: Least Squares - B733/4/5

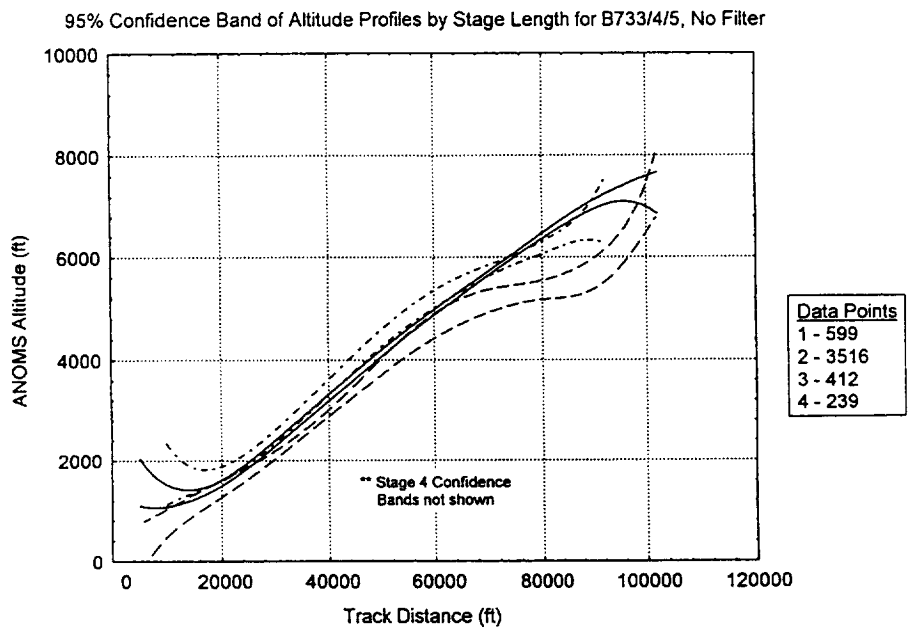

Figure B9. Departure Altitudes: Confidence Limits - B733/4/5

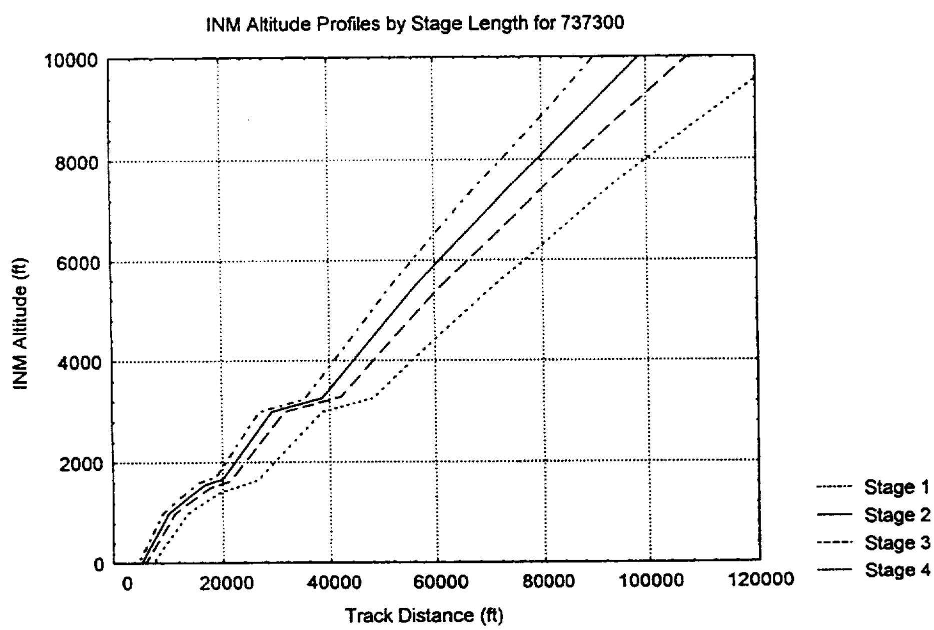

Figure B10. Departure Altitudes: INM - B737300

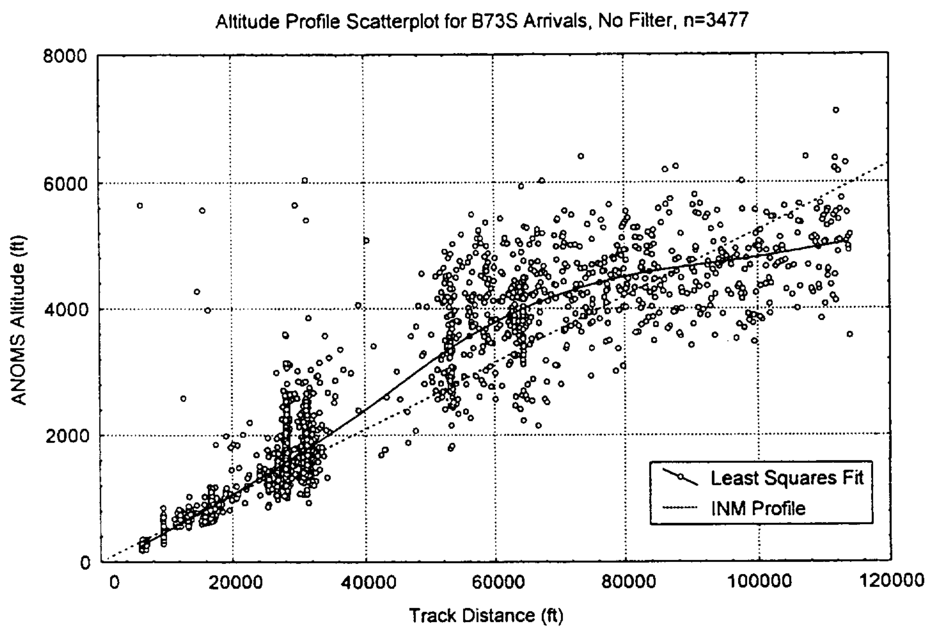

Figure B11. Arrival Altitudes: Measured Least Squares, INM - B73S

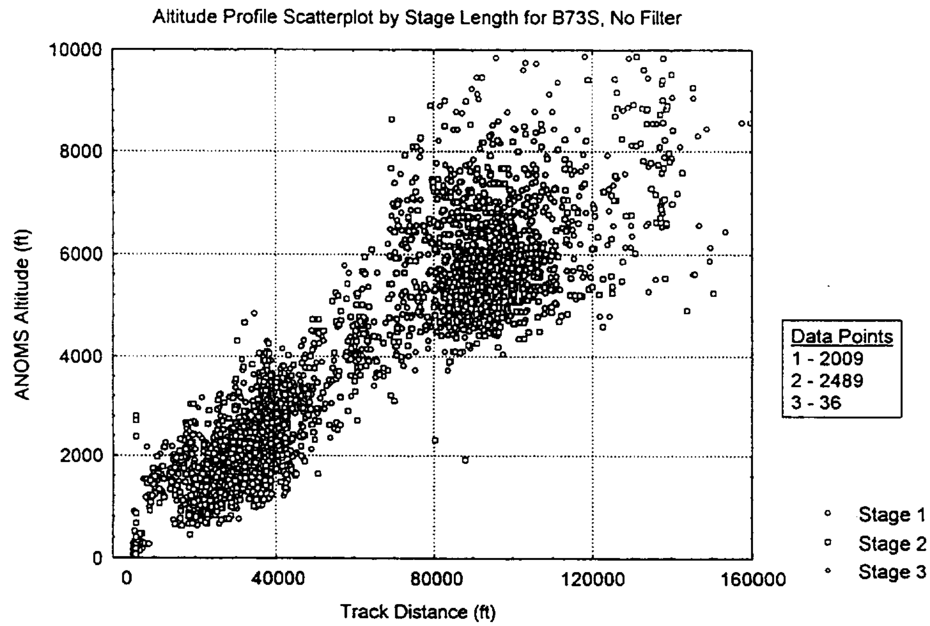

Figure B12. Departure Altitudes: Measured by Stage Length - B73S

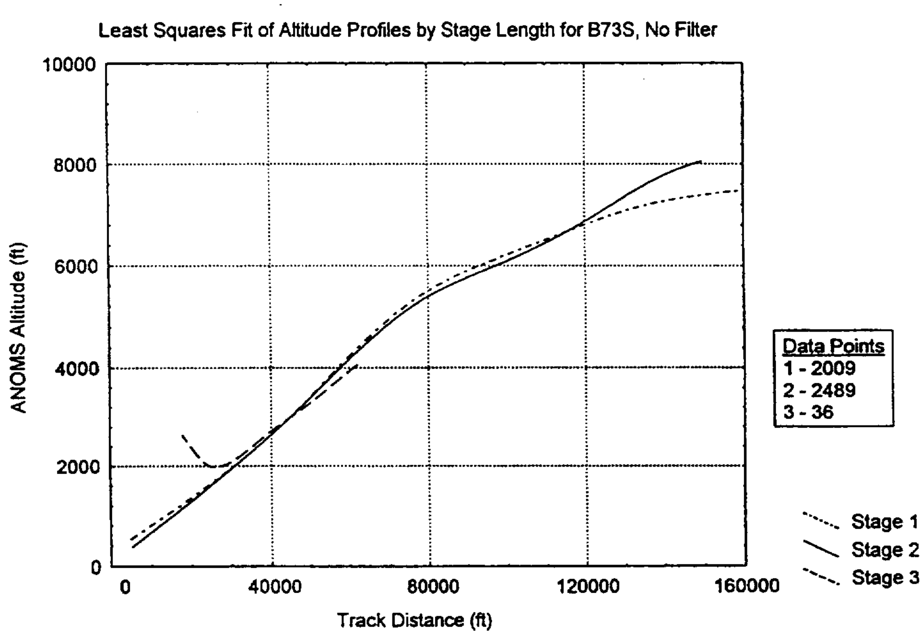

Figure B13. Departure Altitudes: Least Squares - B73S

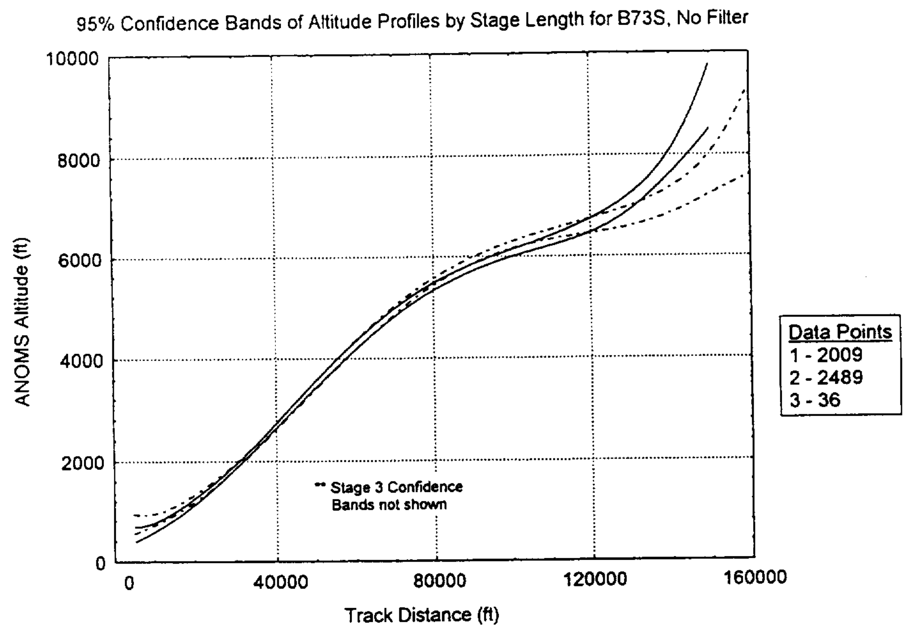

Figure B14. Departure Altitudes: Confidence Limits - B73S

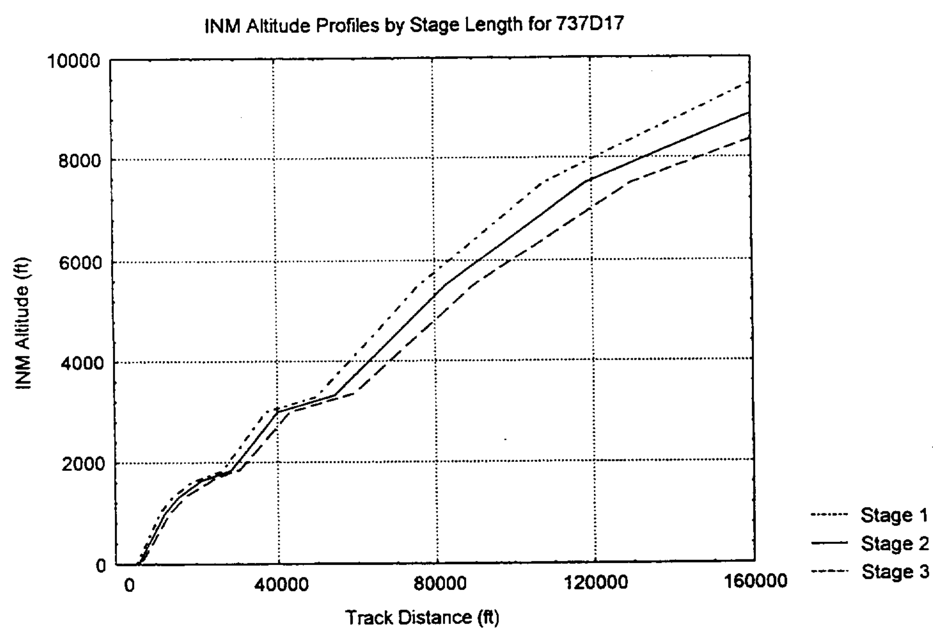

Figure B15. Departure Altitudes: INM - B737D17

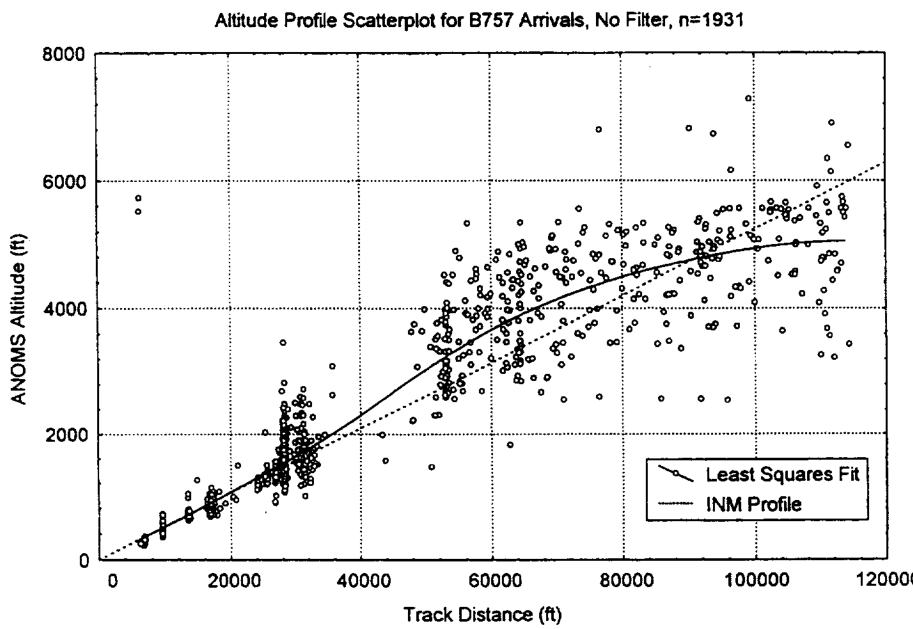

Figure B16. Arrival Altitudes: Measured, Least Squares, INM - B757

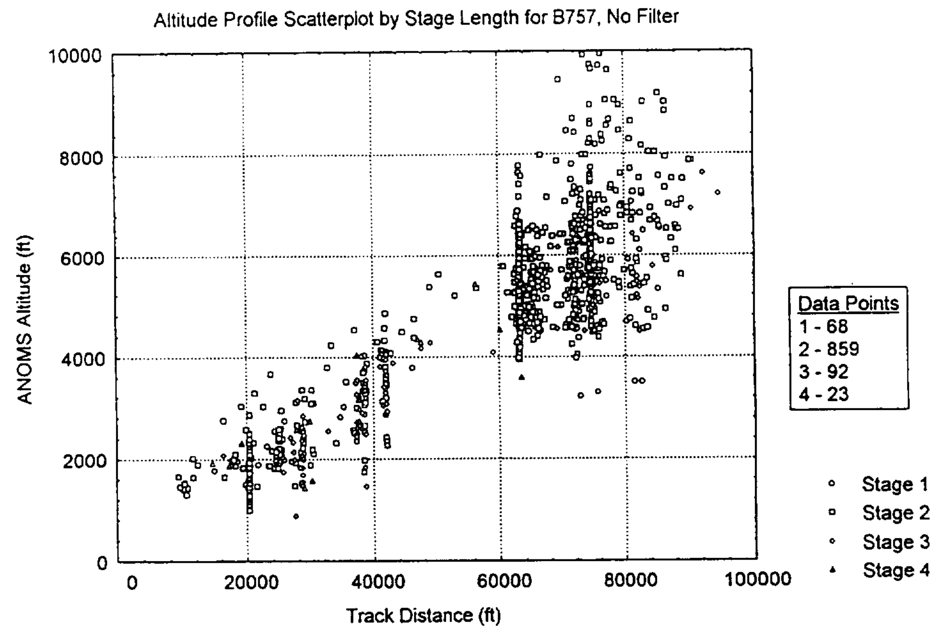

Figure B17. Departure Altitudes: Measured by Stage Length - B757

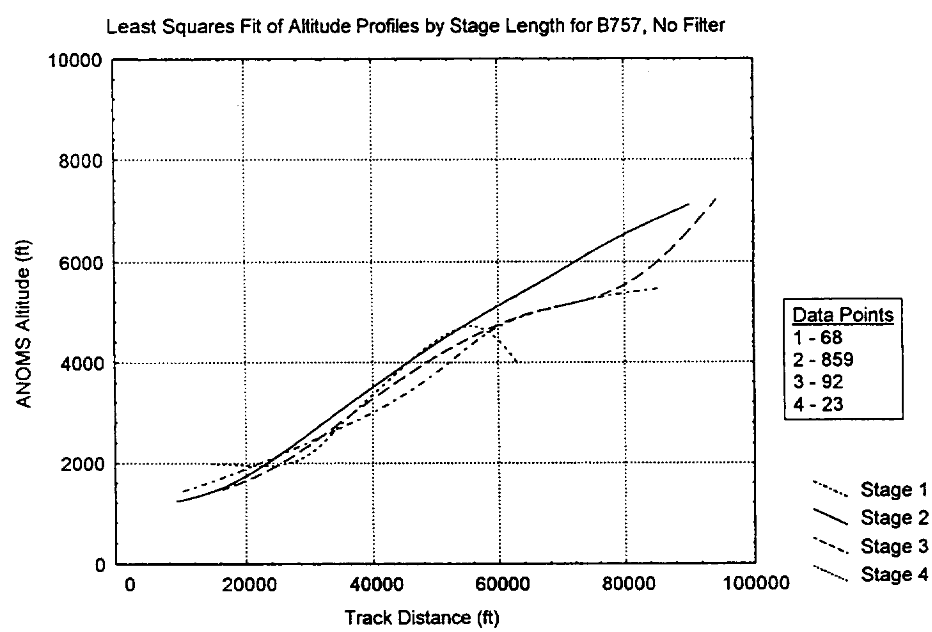

Figure B18. Departure Altitudes: Least Squares - B757

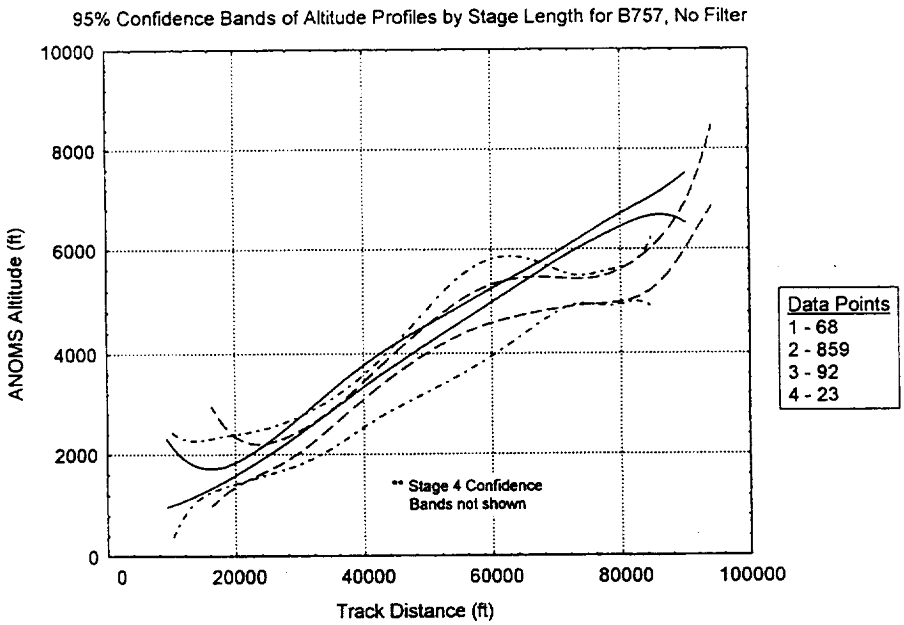

Figure B19. Departure Altitudes: Confidence Limits - B757

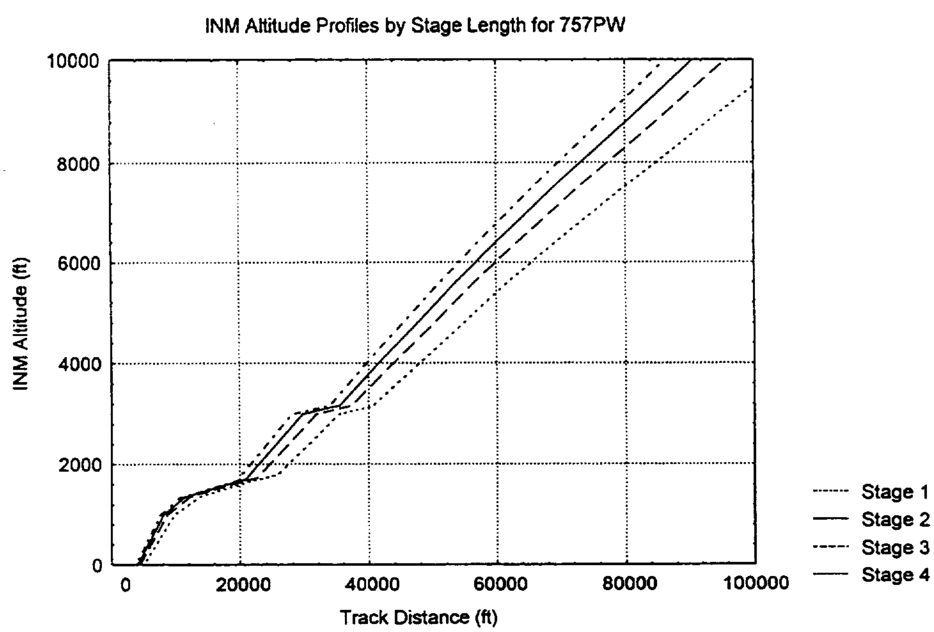

Figure B20. Departure Altitudes: INM - B757PW

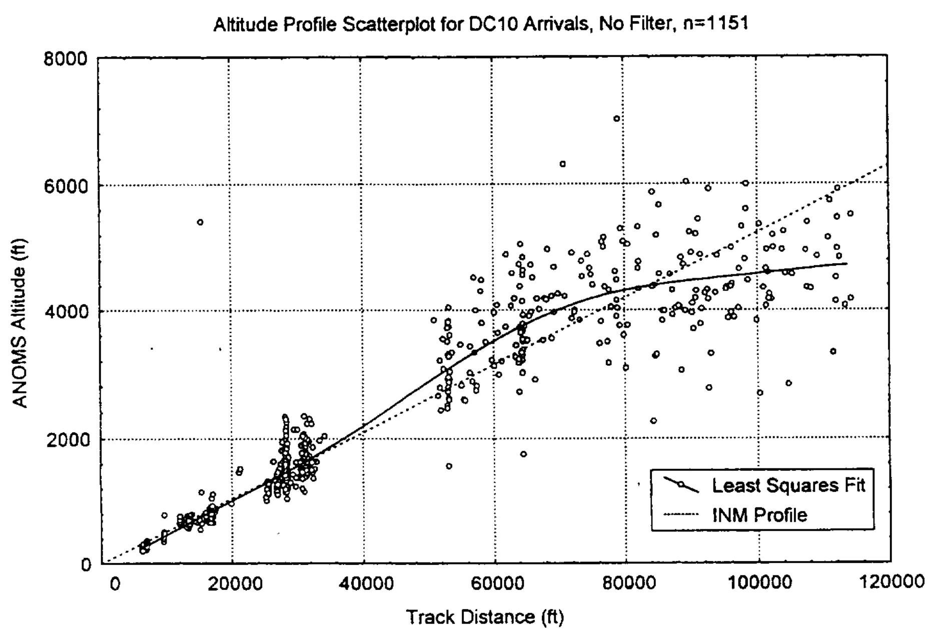

Figure B21. Arrival Altitudes: Measured, Least Squares, INM - DC10

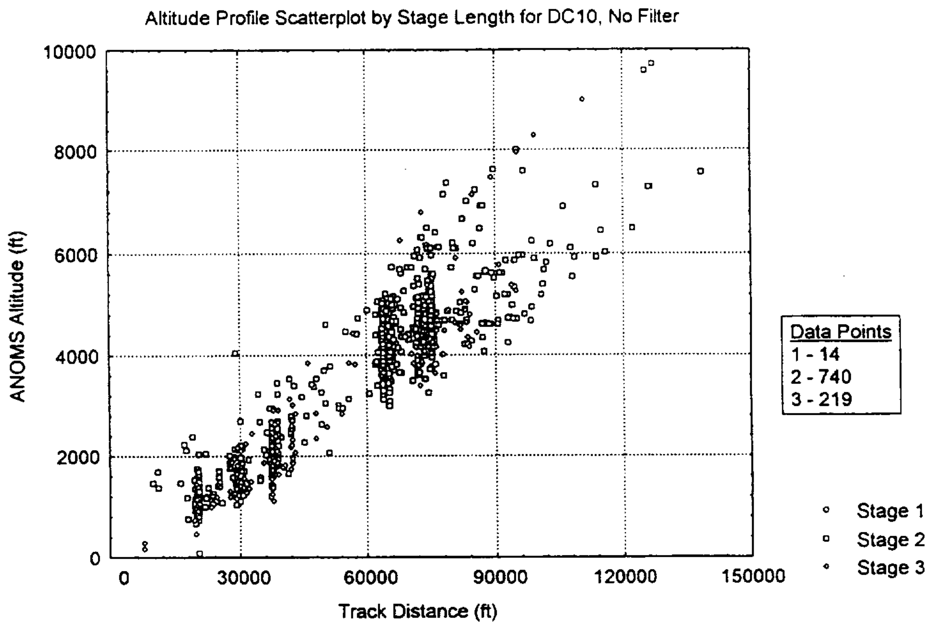

Figure B22. Departure Altitudes: Measured by Stage Length - DC10

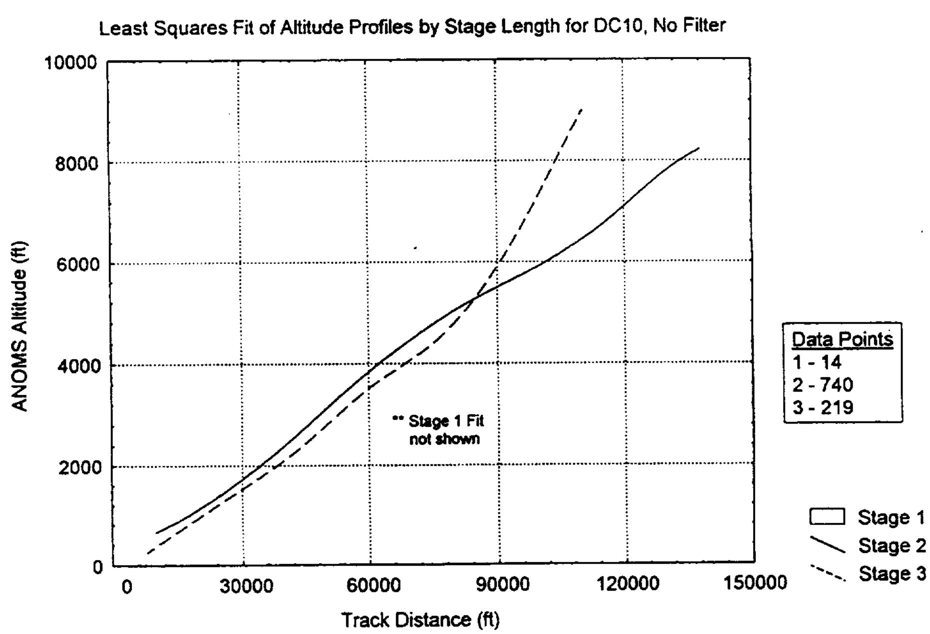

Figure B23. Departure Altitudes: Measured Least Squares - DC10

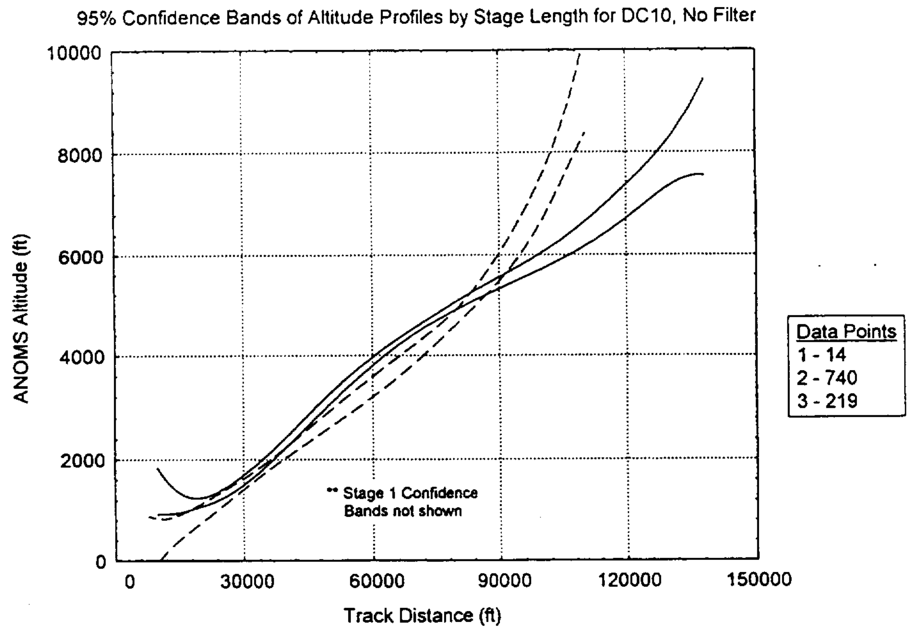

Figure B24. Departure Altitudes:Confidence Limits - DC10

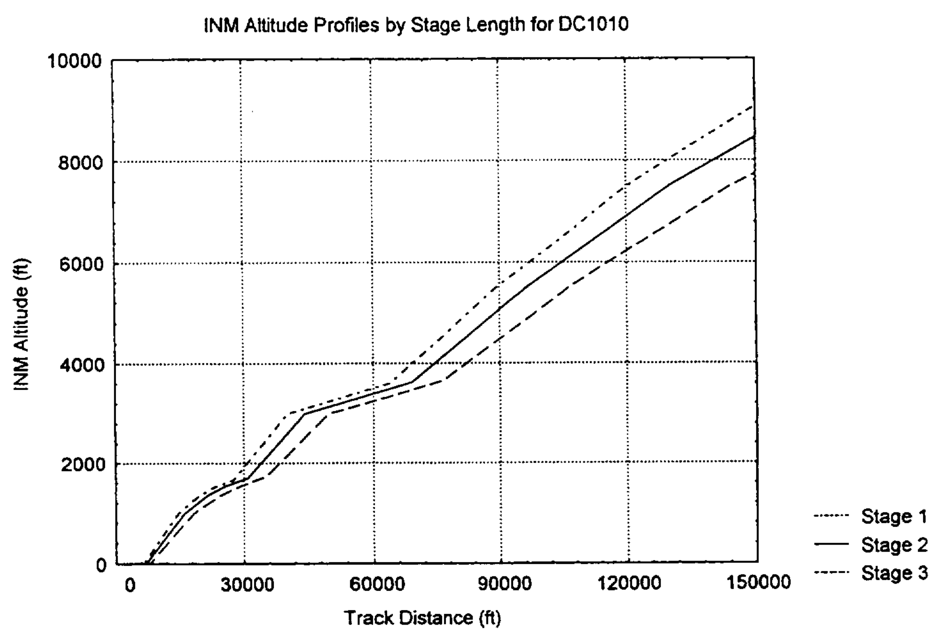

Figure B25. Departure Altitudes: INM - DC1010

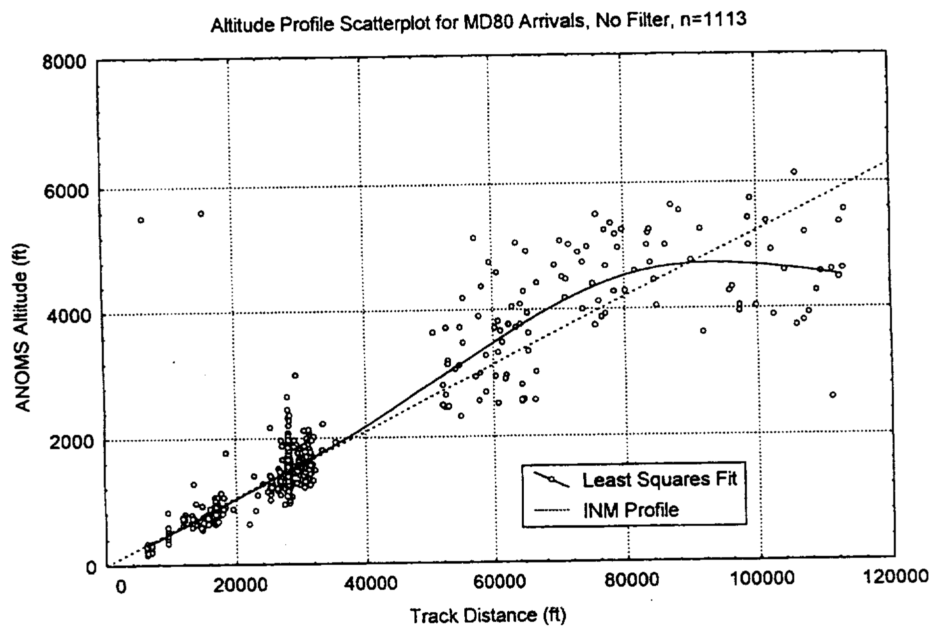

Figure B26. Arrival Altitudes: Measured, Least Squares - MD80

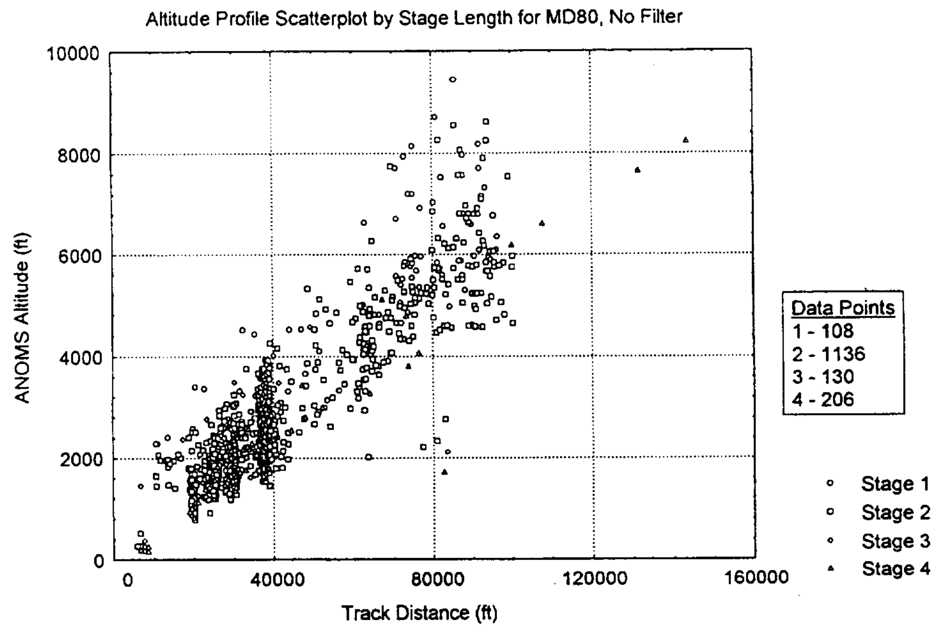

Figure B27. Departure Altitudes: Measured by Stage Length - MD80

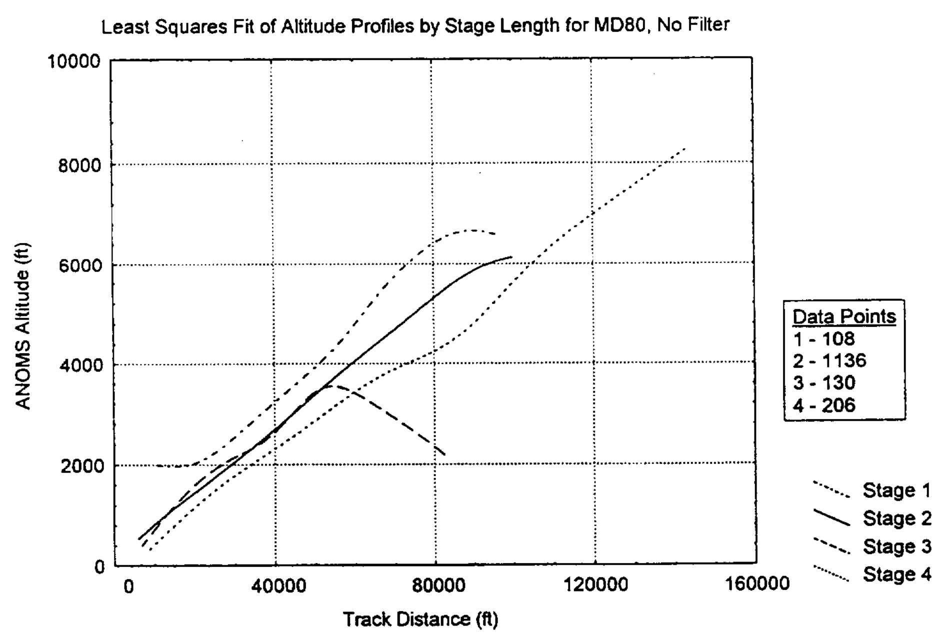

Figure B28. Departure Altitudes: Least Squares - MD80

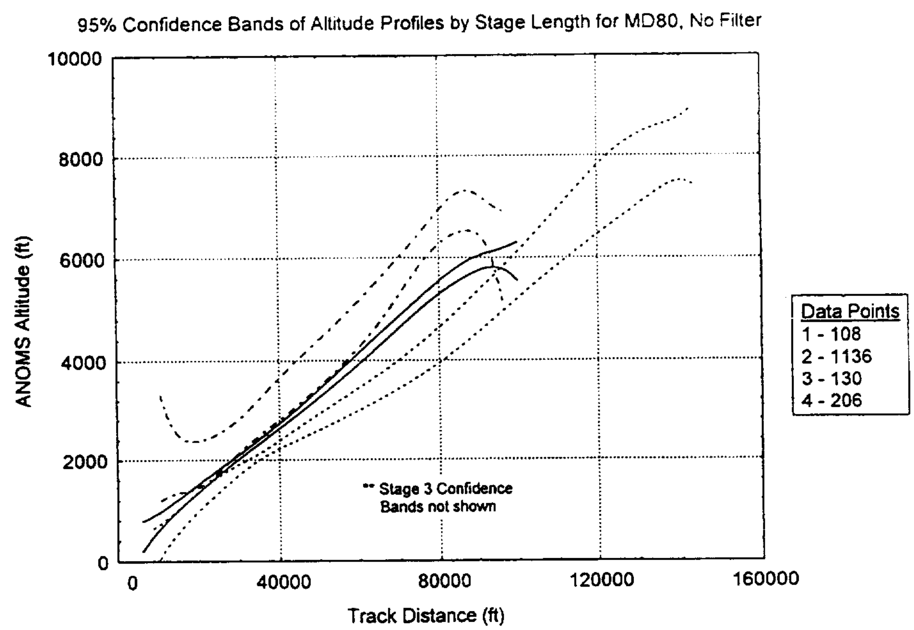

Figure B29. Departure Altitudes: Confidence Limits - MD80

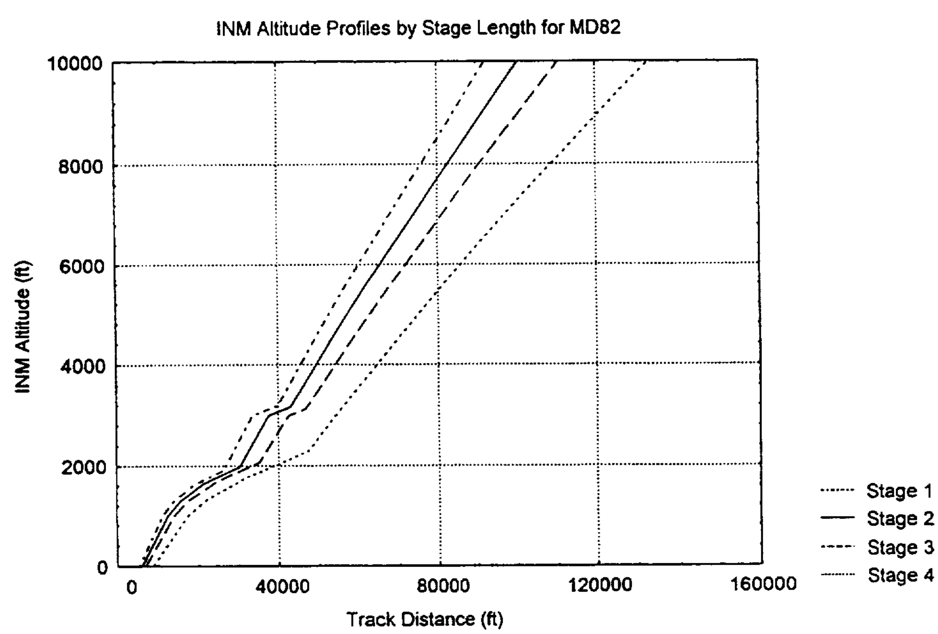

Figure B30. Departure Altitudes: INM - MD 83

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2000	Contractor Report

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Examining INM Accuracy Using Empirical Sound Monitoring and Radar Data	C NAS1-20102 WU 538-03-15-01
6. AUTHOR(S) Nicholas P. Miller, Grant S. Anderson, Richard D. Horonjeff, Sebastian Kimura, Jonathan S. Miller, David A. Senzig, and Richard H. Thompson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Harris Miller Miller & Hanson, Inc. (HMMH) 15 New England Executive Park Burlington, MA 01803	8. PERFORMING ORGANIZATION REPORT NUMBER HMMH Rpt. No. 294520.03
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Langley Research Center Hampton, VA 23681-2199	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA/CR-2000-210113

11. SUPPLEMENTARY NOTES

Langley Technical Monitor: Kevin P. Shepherd

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Unclassified-Unlimited Subject Category 71 Distribution: Nonstandard Availability: NASA CASI (301) 621-0390	

13. ABSTRACT (*Maximum 200 words*)

Aircraft noise measurements were made using noise monitoring systems at Denver International and Minneapolis St. Paul Airports. Measured sound exposure levels for a large number of operations of a wide range of aircraft types were compared with predictions using the FAA's Integrated Noise Model. In general it was observed that measured levels exceeded the predicted levels by a significant margin. These differences varied according to the type of aircraft and also depended on the distance from the aircraft. Many of the assumptions which affect the predicted sound levels were examined but none were able to fully explain the observed differences.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Noise - Aircraft Noise Prediction	133
	16. PRICE CODE A07

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL